# *In situ* noble metal $YBa_2Cu_3O_7$ thin-film contacts

J. W. Ekin, S. E. Russek, C. C. Clickner, and B. Jeanneret
*Electromagnetic Technology Division, National Institute of Standards and Technology, Boulder, Colorado 80303*

(Received 20 August 1992; accepted for publication 9 November 1992)

Thin-film contacts to $YBa_2Cu_3O_7$ have been fabricated by an *in situ* noble-metal process and patterned down to $2\times2$ $\mu m^2$; at this small size, the contacts carry transport current over $10^6$ A/cm$^2$ while maintaining a specific contact resistivity $\rho_c$ in the $10^{-8}$ to $10^{-9}$ $\Omega$ cm$^2$ range. No oxygen annealing was used in the processing, thus avoiding the problem of silver or gold agglomeration, as well as preserving a sharp interface for Josephson-device applications. $\rho_c$ was measured to increase only $\sim$25% as temperature was increased from 4 to 90 K. The measurements were carried out on a series of film morphologies using both superconductor-normal metal and superconductor-normal metal-superconductor test structures; a carefully designed test pattern was used to correct for spreading conduction in the noble-metal contact layer. The contacts were ohmic with voltage-current characteristics that were linear over more than four orders of magnitude.

This letter reports thin-film high $T_c$ contact resistivities $\rho_c$ in the $10^{-8}$ to $10^{-9}$ $\Omega$ cm$^2$ range for micrometer-size noble metal contacts fabricated by an *in situ* process without oxygen annealing ($\rho_c \equiv RA$, the product of the contact resistance $R$ and contact area $A$). The low value of $\rho_c$ was obtained in both gold and silver thin-film contacts patterned down to sizes less than $2\times2$ $\mu m^2$ [using both superconductor-normal metal (SN) and superconductor-normal metal-superconductor (SNS) test patterns]. Furthermore, $\rho_c$ was maintained in this low range at contact current densities over $10^6$ A/cm$^2$. This is the first report of planar contacts with $\rho_c$ contact and current capacity all in a practical range for high-density microelectronic circuits.

We also show that this low value of $\rho_c$ is obtained over the entire working temperature range for high $T_c$ superconductors. Using the SN test structure, we measured only a 25% increase in $\rho_c$ from 4 to 90 K. This is significant for a number of high $T_c$ applications that will need to operate in the higher temperature range.

The *in situ* technique consists of depositing a noble-metal film on a high $T_c$ superconducting film without breaking vacuum or intermediate processing (hence the name *in situ* contact). This is just a special case of the low-temperature noble-metal contact method[1] except that the surface-cleaning step is eliminated by preventing the as-grown superconductor surface from degrading in the first place. This was anticipated[1] before *in situ* thin films of $YBa_2Cu_3O_7$ (YBCO) were actually fabricated; now with the development of *in situ* YBCO films, the *in situ* contact process is readily accomplished. Two earlier studies that used this *in situ* contact method demonstrated the process for larger contact sizes [$10^6$ $\mu m^2$ with Au (Ref. 2) and 100 $\mu m^2$ with Ag (Ref. 3)]; no temperature dependence or current densities were reported.

In previous *ex situ* deposited thin-film contacts,[4] oxygen annealing was required to obtain values of $\rho_c$ below about $10^{-6}$ $\Omega$ cm$^2$. Here, we emphasize that these low resistivity results were obtained without oxygen annealing. This eliminates the common problem of agglomeration of the thin-noble metal film into spheres[5] and also minimizes diffusion of the noble metal into the superconductor surface, thus preserving a sharp noble-metal/superconductor interface for Josephson devices.

The contacts were fabricated by first growing an epitaxial YBCO film by magnetron sputtering from a single stoichiometric target using a standard YBCO *in situ* thin-film growth process.[6] The YBCO films were of high quality; the zero-resistance $T_c$'s ranged from 88 to over 90 K; critical-current densities were typically over $10^6$ A/cm$^2$ at 77 K. The YBCO film was then cooled slowly to room temperature in $4\times10^4$ Pa (300 Torr) oxygen. Either gold or silver contact layers between 50 and 100 nm thick were deposited. The noble-metal deposition was carried out with the superconductor film at room temperature with no intermediate exposure to air; the oxygen was evacuated to about $1.3\times10^{-4}$ Pa ($10^{-6}$ Torr) over $\sim$15 min, after which the noble-metal contact layer was deposited using either sputtering (in 5 to 10 mTorr Ar) or resistive-heater evaporation.

Planar contacts were patterned with two different types of contact-test patterns, each consisting of a series of four contact sizes ranging from $16\times16$ $\mu m^2$ down to $2\times2$ $\mu m^2$. For the first test structure, similar to that used earlier in another study,[7] we simply patterned a series of window sizes in an $\sim$1-$\mu$m-thick photoresist layer [see Fig. 1(a)], and then deposited a Pb counterelectrode to form a SNS test structure. In addition, we also formed SN test structures by using the photoresist insulator to simply lift off the superconducting Pb counterelectrode and replace it with a relatively thick (1 $\mu$m) Ag layer. In this way, we were able to easily fabricate both SN and SNS test structures in proximity on the *same* film.

The spreading conductance of the *in situ* Ag or Au layer in the first geometry tends to give apparent $\rho_c$'s that are lower than the actual $\rho_c$. Two-dimensional spreading resistance calculations for this geometry show that the effective contact radius is $r+\xi$, where $r$ is the lithographic contact radius and $\xi \simeq (\rho_c/R_\square)^{0.5}$ ($R_\square$ is the sheet resistance of the *in situ* Ag or Au layer). At 77 K, $\rho_c/\rho_{c\ \mathrm{apparent}} \sim 2$ for the $16\times16$ $\mu m^2$ contacts. To eliminate the

 0003-6951/93/040369-03$06.00  

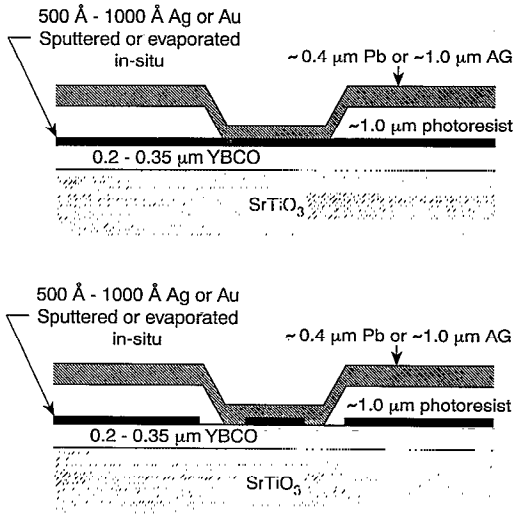


FIG. 1. Contact test geometries: (a) Window made in photoresist insulating layer with replaceable counter electrode of Pb or Ag. (b) Patterned *in situ* contact pad within photoresist window to eliminate spreading conductance into the surrounding *in situ* noble metal region (shown as black region in figure).

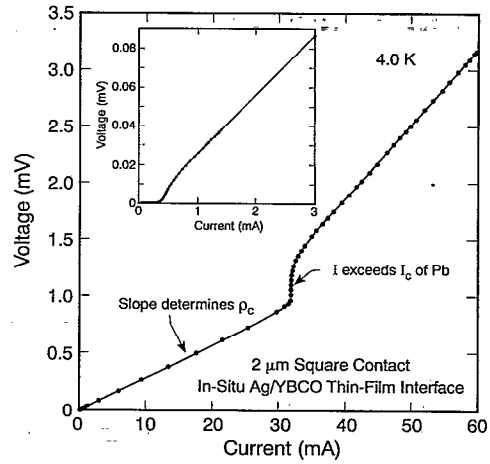


FIG. 2. Voltage vs current characteristic of $2\times2$ $\mu m^2$ *in situ* Ag/YBCO contact showing 0.4 mA supercurrent (insert) and extensive ohmic region to more than 30 mA ($>10^6$ A/cm$^2$ transport current density through contact) before reaching the $J_c$ of the Pb counterelectrode. Values of the specific contact resistivity $\rho_c$ given in Table I were determined from this extensive linear region.

need to correct for spreading resistance, we also formed a second test structure on the same films by lifting off the earlier deposited counter electrode and depositing and patterning a second contact-test pattern. The second test structure differed from the first in that a perimeter of *in situ* noble metal was removed to isolate the contact pad [see Fig. 1(b)]. (Conduction between the counterelectrode and the exposed YBCO perimeter around the *in situ* contact pad was not a factor since this interface was formed after *ex situ* processing; indeed, $\rho_c$ for the *ex situ* interface was measured in a separate experiment to be about 100 times greater than $\rho_c$ for the *in situ* interface. Several control test structures were also fabricated without contact windows to ensure there was no pinhole shorting through the photoresist insulation layer.)

High-sensitivity voltage measurements across the contact interface were carried out to the 100 pV level. Figure 2 shows a contact *V-I* characteristic for a $2\times2$ $\mu m^2$ *in situ* contact between a partial *a*-axis YBCO film and a Pb counterelectrode. There is a supercurrent of $\sim0.4$ mA followed by a linear resistive region that extends out to $\sim32$ mA where $J_c$ of the Pb film is exceeded. This extensive linear region was used to determine the specific contact resistivity $\rho_c$ for all the contacts; the results are presented at 4 K for each film in the last two columns of Table I (one for each test geometry). Note that the second geometry which omits spreading conductance, consistently resulted in a $\rho_c$ value that is about double the value of $\rho_c$ of the simple window geometry in agreement with calculation.

As shown in Table I, $\rho_c$ at 4 K is in the $10^{-9}$ to $10^{-8}$ $\Omega$ cm$^2$ range for both geometries. This is adequate for package interconnects and is approaching the range needed for multichip modules. With oxygen annealing, these $\rho_c$ values might be reduced further. Similar results were obtained for both SN and SNS contact configurations. Except for the partial *a*-axis film, no supercurrents were observed. The *V-I* characteristics were linear over more than four orders of magnitude indicating high-quality contacts that are *ohmic* in character.

There was no correlation with the elapsed time between formation of the YBCO and deposition of the *in situ* noble metal layer at room temperature, as seen in Table I, but then, no correlation was expected for such relatively high background pressure. Some correlation with morphology was observed with the smooth *c*-axis and partial *a*-axis morphology generally giving the lowest values of $\rho_c$.

Theoretically, the *a,b*-axis conduction is $\sim1000$ times greater than the *c*-axis conduction.[8] For the smooth *c*-axis films, we find from scanning tunneling microscopy[9] that the exposed Cu-O plane edge area is about 1000 times less than the *c*-axis area. Therefore, we would expect the *a,b*-axis conduction to be comparable to the *c*-axis conduction in the smooth *c*-axis films, resulting in about a factor of 2 difference in $\rho_c$. However, for the partial *a*-axis film and the *c*-axis films with extensive pitting, we would expect considerably more of an effect from the *a,b*-axis conduction and a significantly lower $\rho_c$ than for the smooth *c*-axis films, which was not observed. Consequently, there may well be a degraded surface layer at the Cu-O plane edges.

From a practical standpoint, however, the results are very encouraging since $\rho_c$'s down in the $10^{-9}$–$10^{-8}$ $\Omega$ cm$^2$ range were obtained for patterned, planar contacts on typical *c*-axis grown YBCO films without a particularly low background pressure [$\sim1.3\times10^{-4}$ Pa ($10^{-6}$ Torr)]. As seen in Table I, $\rho_c$'s in this range were obtained for both Ag and Au contacts. Also, both evaporation and sputter deposition of the *in situ* noble-metal layer appear to work.

The $\rho_c$ results given in Table I were obtained at liquid-helium temperature. What happens at higher temperatures? With the SN test structure, we measured the temperature dependence of the contact resistivity over the temperature range from 295 down to 4 K. At $T_c$, there was a sharp decrease in $\rho_c$ as the YBCO film became supercon-

TABLE I. *In situ* noble metal YBCO thin-film contacts.

| Film | Contact material (nm) | Deposition method | YBCO morphology | Background pressure ($10^{-6}$ Torr) | Time[a] (min) | $T_{co}$[b] (K) | $J_c$ (76 K) 0.1 $\mu$V criterion[c] ($10^6$ A/cm$^2$) | $\rho_c$ (4 K) ($\Omega$ cm$^2$) | Geom. omitting spreading cond. $\rho_c$ (4 K) ($\Omega$ cm$^2$) |
|---|---|---|---|---|---|---|---|---|---|
| 4S12 | 100 Ag | evaporation | smooth *c* axis, no pits, boulders | 0.95 | 65 | 90.3 | 1.25 | $3.9\times10^{-9}$ | $8\times10^{-9}$ |
| 4S11 | 100 Ag | evaporation | partial *a* axis, no pits | 0.2 | 77 | 88.8 | 1.4 | $7.1\times10^{-9}$ | $1.5\times10^{-8}$ |
| 4S14 | 100 Au | evaporation | *c* axis, pits, boulders, small amount *a* axis | 1.5 | 47 | 89.8 | 0.59 | $1.0\times10^{-8}$ | $2.8\times10^{-8}$ |
| 4S13 | 100 Au | evaporation | *c* axis, pits, and boulders | 3.3 | 42 | 89.8 | 1.7 | $1.5\times10^{-8}$ | $3.1\times10^{-8}$ |
| 4S16 | 50 Au | sputter | rough texture | 0.87 | 150 | 88.2 | 0.43 | $3.9\times10^{-8}$ | ··· |

[a]Time between end of YBCO deposition and start of noble-metal deposition.
[b]Zero-resistance temperature.
[c]Along 1.5 mm length.

ducting, as shown in Fig. 3. Below $T_c$, where the resistance of the YBCO/*in situ* metal interface is dominant, $\rho_c$ monotonically decreased about 25%, indicating a metalliclike contact interface. Thus, $\rho_c$'s of the same quality, as shown in Table I at 4 K, are characteristic of these contact interfaces over the entire temperature range below 90 K.

In summary, these are the first high-sensitivity contact data in a well-defined measurement geometry to show that:

(1) Either silver or gold thin-film planar contacts suitable for microelectronic connections can be obtained with $\rho_c$'s in the $10^{-9}$ to $10^{-8}$ $\Omega$ cm$^2$ range without oxygen annealing by using the *in situ* thin-film contact process.

(2) Contact current densities over $10^6$ A/cm$^2$ can be obtained in nominal *c*-axis planar contacts down to sizes of $2\times2$ $\mu$m$^2$.

(3) Varying the temperature from 4 to 90 K produced only a $\sim$25% increase in $\rho_c$.

(4) Comparable $\rho_c$ values were obtained for both SN and SNS interface structures.

Existing YBCO deposition equipment can be fairly easily modified to incorporate deposition of the *in situ* noble metal buffer layer, either with the addition of a resistive evaporation source, a second sputtering gun, or an additional noble-metal target for laser ablation systems. Because of the energy of the particles in laser ablation, an inert gas, such as 27 Pa (200 mTorr) of Ar, is needed to avoid resputtering.[10] Also, laser ablation rates are about two orders of magnitude lower for noble metals than for YBCO, but this can be compensated for by operating at a higher laser pulse rate, raising the power per pulse, or increasing the beam aperture. Deposition time is still relatively short, however, because an *in situ* noble metal layer of only several tens of nanometers is needed for an effective contact interface.

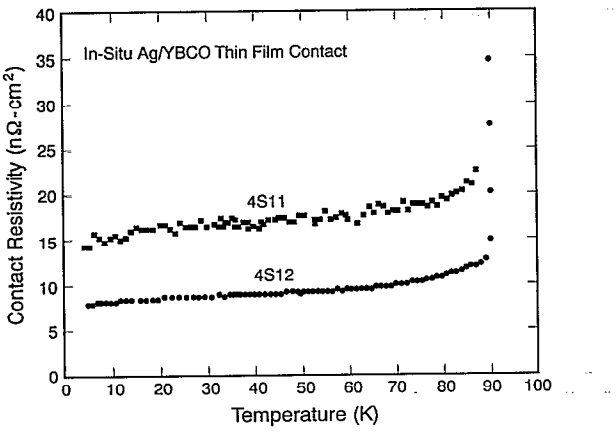


FIG. 3. Temperature dependence of specific contact resistivity $\rho_c$, showing only a 25% rise in $\rho_c$ of high-quality *in situ* contacts from 4 to 90 K.

We wish to thank S. Wolf, D. Rudman, S. Sanders, and F. R. Fickett for helpful discussions and editorial comments. This work was supported by DARPA under Contract 7975-01 and the NIST high $T_c$ program.

[1]Method for Making Low Resistance Contacts to High-$T_c$ Metal Oxide-Superconductors, J. W. Ekin and A. J. Panson, patent disclosure filed with U.S. Dept. of Commerce, June 15, 1987, issued as U.S. No. 4,963,523; see also, J. W. Ekin, A. J. Panson, and B. A. Blankenship, Appl. Phys. Lett. **52**, 331 (1988).
[2]J. R. Gavaler and A. I. Braginski, Physica C **153-155**, 1435 (1988); A. I. Braginski, J. Talvacchio, J. R. Gavaler, M. G. Forrester, and M. A. Janocko, SPIE **948**, 89 (1988).
[3]M. S. Wire, R. W. Simon, J. A. Luine, K. P. Daly, S. B. Coons, A. E. Lee, R. Ju, J. F. Burch, and C. E. Platt, IEEE Trans. Magn. **27**, 3106 (1991).
[4]See, for example, J. W. Ekin, T. M. Larson, N. F. Bergren, A. J. Nelson, A. B. Swartzlander, L. L. Kazmerski, A. J. Panson, and B. A. Blankenship, Appl. Phys. Lett. **52**, 1819 (1988); Y. Tzeng, A. Holt, and R. Ely, *ibid.* **52**, 155 (1988); J. Talvacchio, IEEE Trans. Components, Hybrids Manuf. Technol. **12**, 21 (1989).
[5]A. Roshko, R. H. Ono, J. A. Beall, J. Moreland, A. J. Nelson, and S. E. Asher, IEEE Trans. Magn. **27**, 1616 (1991).
[6]S. E. Russek, B. Jeanneret, D. A. Rudman, and J. W. Ekin, IEEE Trans. Magn. **27**, 931 (1991).
[7]M. Lee, D. Lew, C.-B. Eom, T. H. Geballe, and M. R. Beasley, Appl. Phys. Lett. **57**, 1152 (1990).
[8]M. Yu. Kupriyanov and K. K. Likharev, IEEE Trans. Magn. **27**, 2460 (1991).
[9]John Moreland, Paul Rice, S. E. Russek, B. Jeanneret, A. Roshko, R. H. Ono, and D. A. Rudman, Appl. Phys. Lett. **59**, 3039 (1991).
[10]R. H. Ono, J. A. Beall, M. W. Cromar, T. E. Harvey, M. E. Johansson, C. D. Reintsema, and D. A. Rudman, Appl. Phys. Lett. **59**, 1126 (1991).