LBL-35678
UC-426

Submitted to
Surface and Coatings Technology

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R. A. MacGill, S. Anders, A. Anders, R. A. Castro,
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Lawrence Berkeley Laboratory, University of California,
Berkeley, CA 94720

May 23, 1994

This work was supported by the Electric Power Research Institute under Contract RP 8042-03, and the U.S. Department of Energy, Division of Advanced Energy Projects, under Contract No. DE-AC03-76SF00098.

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Abstract

Black CuO films are used for improved radiation cooling of, e.g., an RF kicker at the Advanced Light Source of Lawrence Berkeley Laboratory. The films are required to be transparent to RF fields particularly in the range 1-1.25 GHz, UHV compatible, and very adhesive even after a number of baking cycles. Usual techniques such as wet-chemical coating do not fulfill the requirements for UHV compatibility. A cathodic arc plasma source with a copper cathode was operated in an oxygen atmosphere to form CuO films on the substrate which was either at the same time the anode or was mounted on a substrate holder. The films are single-phase polycrystalline CuO. They are slightly oxygen rich, adhere very well (pull strength exceeding 85 MPa) and fulfill all UHV requirements. The deposition method is very efficient, and large workpieces up to a surface area of 5000 cm^2 have been coated.

1. Introduction

The radiation properties of CuO are close to those of an ideal black body making it a good coating for applications of enhanced radiation heat transfer of, e.g., RF parts in accelerator devices. For example, the longitudinal feedback kicker of the Advanced Light Source at Lawrence Berkeley Laboratory needs additional cooling to keep its temperature below 100 °C. The kicker is made from aluminum and consists of four RF electrode pairs inside a kicker housing which is a tube of 1 m length. The electrodes are heated by currents induced in the structure by the electron beam, and they transfer this heat mainly by radiation to the kicker housing. The kicker electrodes are exposed to an energy dissipation of 5-10 Watts during operation which leads to an asymptotic temperature increase of the kicker electrodes of up to 150 K. A black coating of the aluminum surfaces can increase the radiation heat transfer considerably and decrease the asymptotic temperature of the device since the spectral emittance of UHV-cleaned aluminum is only about 0.06 at a wavelength of 0.65 μm [1] compared to 1 for an ideal black body. Such a coating has to be transparent to RF radiation particularly over the operating range of 1-1.25 GHz, strongly adherent to aluminum even after a few vacuum baking cycles, non-magnetic and UHV-compatible. A good candidate is CuO with a spectral emittance of about 0.7 [1], but the conventional deposition technique of wet-chemical coating does not form UHV-compatible films and requires complicated masking to prevent destruction of parts which should not be coated. We have applied a cathodic arc deposition technique to form CuO on aluminum which is based on operating a cathodic arc plasma source with a copper cathode in an oxygen atmosphere. This method produces films with a very low contamination level which are well suited for UHV applications. In the present paper we will describe the method and the depositions we have performed, and will further discuss the film properties obtained.

2. Deposition technique

Copper oxide was deposited using a cathodic arc plasma source with a copper cathode (5 cm diameter) operated in an oxygen atmosphere. The oxygen pressure was 300 mTorr. The arc current was 120 A, the arc duration 250 ms, the arc repetition rate 0.5 s^{-1}, and the arc was triggered by a 5 μs long high-voltage spark surface discharge. Two different arrangements were tested for the coating of the outside of the kicker electrodes. Fig. 1(a) shows the cathodic arc plasma source with a cylindrical anode surrounding the cathode whereas Fig. 1(b) shows the arrangement in which the substrate (kicker electrode) was the anode. The films deposited in these two different ways were very similar, but the deposition rate in arrangement (b) was much higher. Therefore we have used the substrate as the anode for coating the outside of kicker electrodes as well as for coating the inside of the kicker housing, see Fig. 1(c). Cathode, substrates and anode of the plasma source (if used) were water-cooled. Areas which should not be coated were covered by metallic masks.

The contamination of the cathodic arc plasma by micron-size droplets (macroparticles) of the cathode material represents a problem for achieving high quality coatings [2]. When operating in a gaseous atmosphere the cathode erosion rate [3, 4] as well as the droplet emission [5, 6] is greatly reduced. In the present experiment a slight contamination of the CuO film by macroparticles can be tolerated as long as the films appear black because a few micron size copper macroparticles do not influence the RF behavior of the device. Since most of the macroparticles are emitted under a flat angle to the cathode surface [7, 8], the macroparticle contamination is low for the deposition arrangements (a) and (b). For the coating of the inside of the kicker housing two additional "droplet catcher plates" made from machineable ceramic were installed on both sides of the cathode to reduce the droplet contamination.

Fig. 2 shows one of the electrodes after coating. The electrodes were mounted on a movable vacuum feedthrough so as to be able to rotate and move the electrode longitudinally. The deposition was performed in three different longitudinal positions in each quadrant. The distance between cathode surface and substrate was 5 cm. The inside of the kicker housing was coated by moving the plasma source through the bore of the housing. Areas inside the bore which were not to be coated were covered by stainless steel masks. Fig. 3 shows the housing after deposition and removing of the masks. The average deposition rate was 5 nm/s over an area of 100 cm^2 for the deposition of the electrodes, and 20 nm/s over an area of 100 cm^2 for the inside of the kicker housing.

To improve the electric contact between the RF power contact surfaces of the kicker and the RF connectors (gold-coated multi contact connectors), the contact surfaces at the electrodes were coated with a thin gold film. Areas which should not be gold coated were covered by metallic masks. A miniature vacuum arc plasma source with a gold cathode was used which was connected to a magnetic macroparticle filter for removing the macroparticles from the plasma. The arc current was 200 A, the duration 5 ms, and the arc repetition rate was 2 s^{-1}. During the exposure to the gold plasma the electrode (substrate) was pulsed-biased to a negative potential of - 1 kV with pulse length of 4 μs and a pulse off-time of 12 μs. During the high-voltage pulses the ions of the gold plasma were accelerated to the substrate and implanted whereas low-energy deposition took place during the high-voltage pulse off-time. This leads to a film which is well intermixed to the substrate at the interface and therefore very adhesive. The method is called "metal plasma immersion ion implantation and deposition", it is described in detail elsewhere [9, 10], and so are the plasma source and macroparticle filter [10, 11].

3. Film characterization

The CuO films were characterized by different methods to verify their chemical composition and structure, adhesion, RF behavior and UHV compatibility.

The chemical composition and thickness of the films was determined by Rutherford Backscattering spectrometry (RBS) using 1.8 MeV hydrogen ions. The films were found to be slightly oxygen-rich with a nominal composition of $CuO_{1.23}$ and a thickness of 5 μm. The crystal structure of the films was studied by X-ray diffraction (XRD) in the Bragg geometry using the Cu Kα line ($\lambda = 0.154$ nm). XRD results on the film deposited in the regime with separate anode and substrate, Fig. 1(a), show low diffraction peak intensities of the CuO phase, Fig. 4(a), although the measured film thickness is 5μm. In addition the CuO diffraction peaks are broad indicating that the CuO grain size in this film is small. Since no diffraction peak of other CuO phases is present, it is believed that this film is mostly amorphous with some small grains of CuO. XRD results on the films deposited in the regime where the substrate is at the same time the anode, Fig. 1(b) and (c), show very strong and sharp diffraction peaks, Fig. 4(b), corresponding to the monoclinic CuO phase. From the width of the peaks, it is estimated that the grain size in these films is about 50 nm.

The coated kicker parts were vacuum baked twice in a furnace at a temperature of 150 °C for 8 hours. No degradation of the films quality was observed after vacuum baking.

Adhesion of the films was measured using a pull tester. For this purpose small aluminum plates were cleaned and coated in the same procedure as the kicker parts using the substrate as the anode. An aluminum pin with a diameter of 2 mm was glued to the films using epoxy, and the pin was pulled normal to the substrate until any of the interfaces ruptured. The pull strength necessary to remove the CuO films from the aluminum substrates exceeded 85 MPa which was the internal strength of the epoxy.

The kicker was tested for RF performance before and after CuO coating. Transmission loss over it's operating range 1-1.25 GHz was identical in both cases. Impedance measurements from 500 MHz to 26 GHz also showed no significant differences indicating that the coating is transparent to RF radiation and well suited for coating of RF devices.

Heating tests were performed with CuO coated aluminum parts which resembled the kicker geometry. The inner electrodes were heated in vacuum (10^{-7} Torr) by varying heating power to simulate the power of the electron beam dissipated into the kicker electrodes during operation, and the temperature rise of the electrode was monitored. The outer housing remained at room temperature. When uncoated, cleaned aluminum parts were used the temperature of the inner electrodes increased by maximum 150 degrees at a heating power of 8 Watts; this temperature increase is not acceptable for kicker operation. After CuO coating of the parts the temperature rise was only 50 degrees which is a value that can be tolerated during kicker operation (Fig. 5). This demonstrates the successful enhancement of thermal radiation heat transfer from the inner electrodes to the outer housing by increased radiation from the black surfaces of the parts.

The kicker was assembled and installed at the Advanced Light Source, and a base pressure of better than 5×10^{-10} Torr has been reached so far.

4. Conclusions

Cathodic arc deposition is an efficient method to form strongly adherent coatings of compound materials with very low contamination and on a large scale. It is an environmentally clean method in comparison to wet-chemical processes since no chemical waste is produced. The films are also cleaner from the chemical point of view, leading to superior UHV compatibility. It is possible to deposit chemical compounds such as oxides

and nitrides as well as pure or alloy metal films using the same type of plasma source which makes the devices very flexible and versatile. As an example we have reported here the successful CuO coating of a longitudinal kicker for the Advanced Light Source at Lawrence Berkeley Laboratory.

Acknowledgments

We wish to thank J. Corlett, J. R. Menenghetti, K. D. Kennedy, M. W. Coleman and J. Johnson for their help, fruitful discussion and advice. This work was supported by the Electric Power Research Institute under Contract RP 8042-03, and the U.S. Department of Energy, Division of Advanced Energy Projects, under Contract No. DE-AC03-76SF00098.

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Figure Captions

Fig. 1: Schematic of the different deposition geometries. (a) Deposition of kicker electrode, plasma source with separate anode was used. (b) Deposition of kicker electrode, electrode is used as anode. (c) Deposition of kicker housing, housing is used as anode.

Fig. 2: Kicker electrode after coating and removing of masks.

Fig. 3: Kicker housing after coating and removing of masks.

Fig. 4: X-ray diffraction spectra for CuO films on aluminum, deposited in a regime shown in Fig. 1(a) for curve (a), and a regime shown in Fig. 1(b) for curve (b).

Fig. 5: Temperature rise as a function of heating power for uncoated and CuO coated kicker parts.

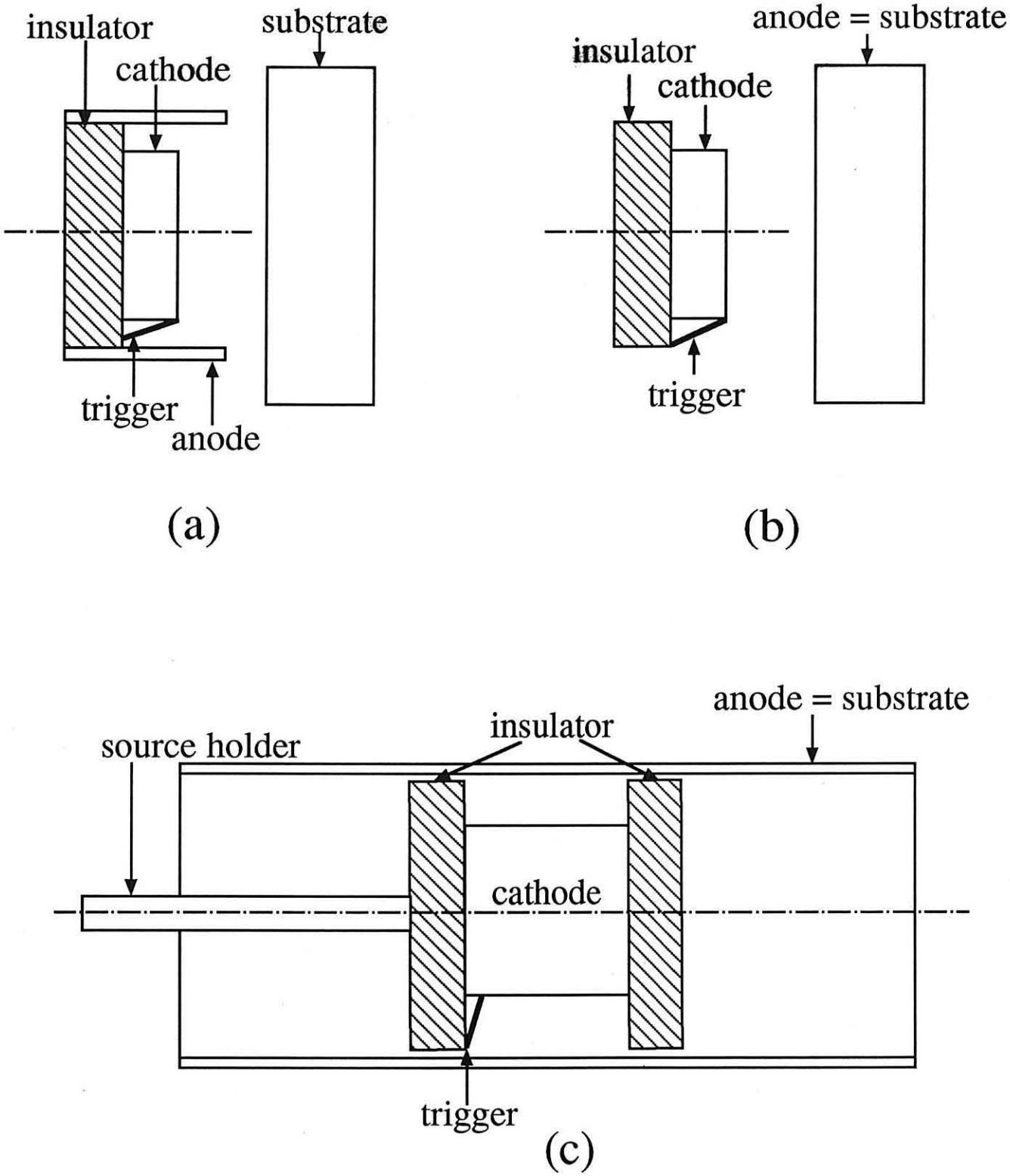
insulator
substrate
cathode
trigger
anode
(a)
anode = substrate
insulator
cathode
trigger
(b)
anode = substrate
insulator
source holder
cathode
trigger
(c)

Fig. 1

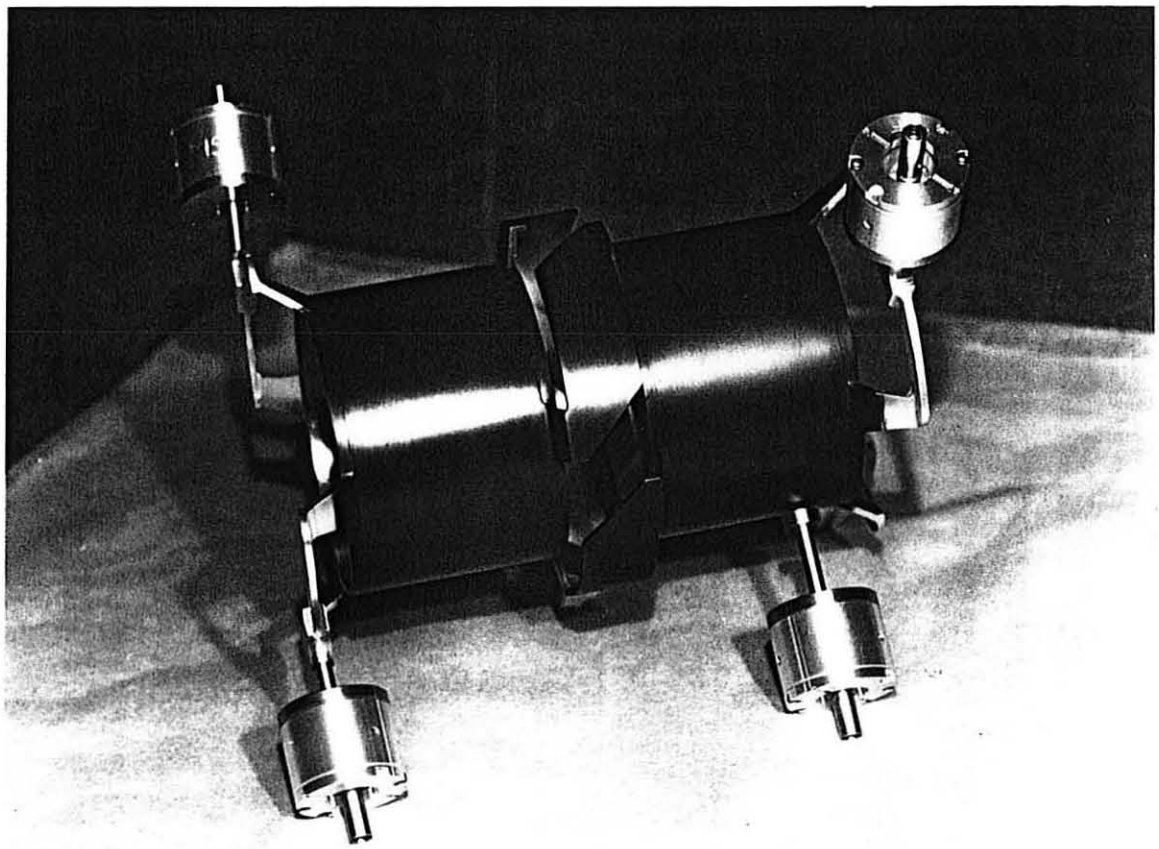

Fig. 2

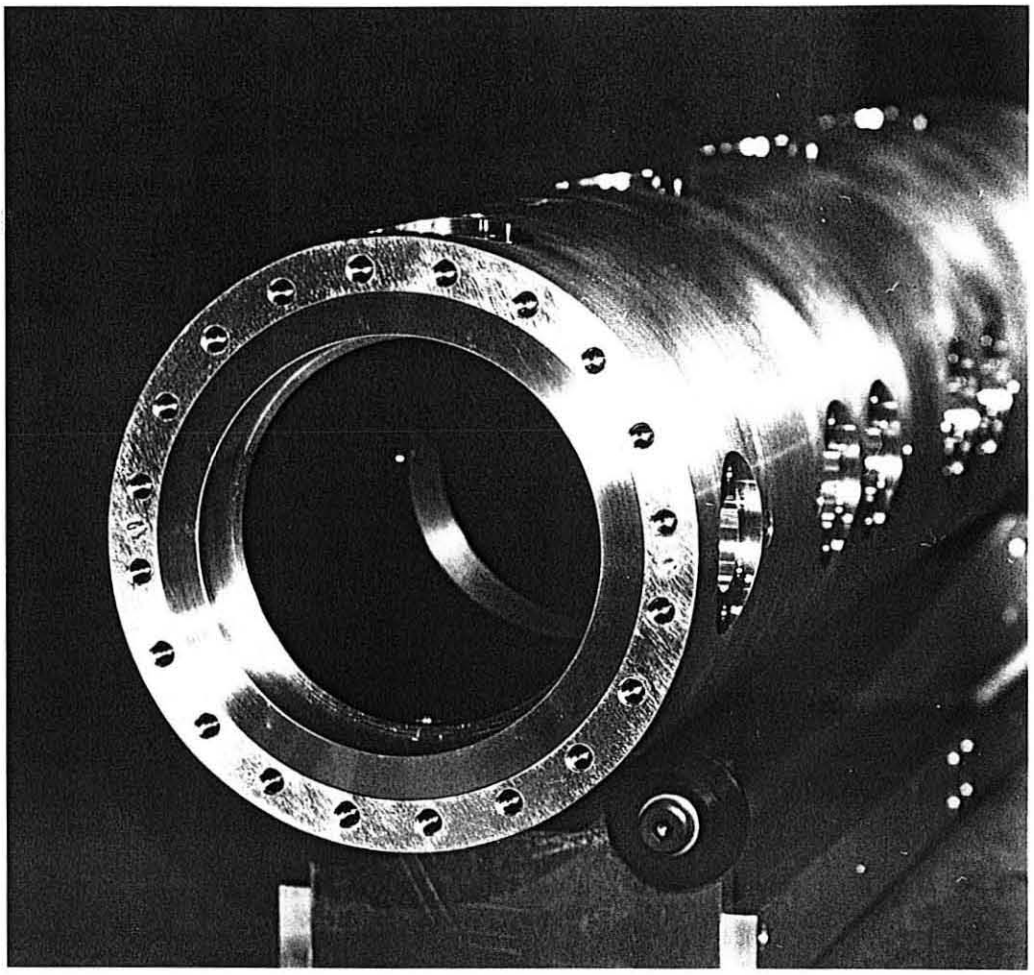

Fig. 3

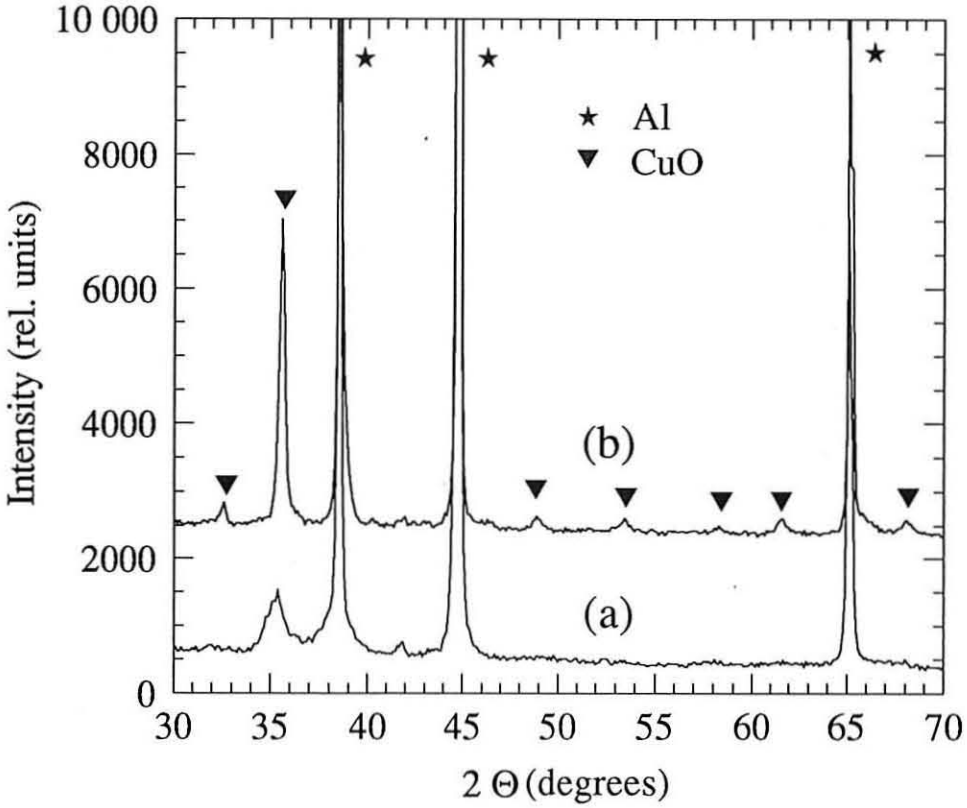
10 000
8000
6000
4000
2000
0
Intensity (rel. units)
30
35
40
45
50
55
60
65
70
2 Θ (degrees)
Al
CuO
(b)
(a)

Fig. 4

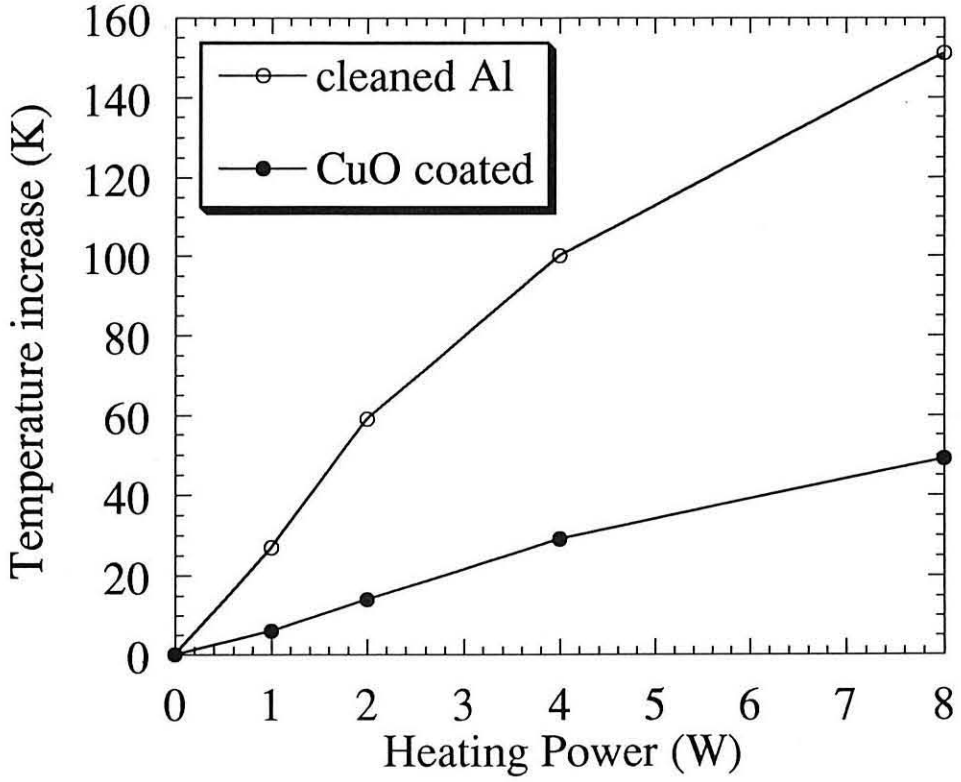
160
140
120
100
80
60
40
20
0
Temperature increase (K)
cleaned Al
CuO coated
0
1
2
3
4
5
6
7
8
Heating Power (W)

Fig. 5