

Multilayer Ti-Cu thin films for the gyroscope housings of the Gravity Probe B Spacecraft

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Abstract

The Gravity Probe B (GP-B) Spacecraft was launched on April 20, 2004. Multilayer Ti-Cu thin films have been coated on the Gravity Probe B gyroscope housings to form the electrostatic suspension electrodes and the support and spin-up lands. The main requirements for these electrode films are low electron field emission, smooth surfaces, good electrical and thermal conductivity, and resistance to arcing damage. The films have been studied by adhesion test, electron field emission, scanning electron microscopy (SEM), and four-point resistivity measurements. 7-layer Ti-Cu films with smooth surfaces, good adhesion and low resistivity have been successfully used for the GP-B gyroscopes, meeting all requirements. The four gyroscopes in the spacecraft instrument performed well during the science data collection of more than one year in Earth orbit.

1. Introduction

The Gravity Probe B (GP-B) Spacecraft was successfully launched on April 20, 2004 into a 642 km polar orbit from Vandenberg Air Force Base, California, USA. The GP-B experiment will test two predictions of the Einstein's theory of General Relativity, the geodetic and frame dragging effects, by measuring the precession of four gyroscopes in Earth orbit [1]. The gyroscope is comprised of a rotor coated with niobium [2] that is electrostatically suspended and spins freely in its gyroscope housing at a temperature of 2 K. Figure 1 is a photograph of the gyroscope rotor and its housing. In previous papers [3,4], we reported that multilayer Ti-Cu thin films had been applied to the GP-B gyroscope housings to form the suspension electrodes, housing support lands to prevent direct rotor-electrode contact, and spin-up lands to reduce helium gas leakage from the gas spin-up channel during gyroscope gas spin up.

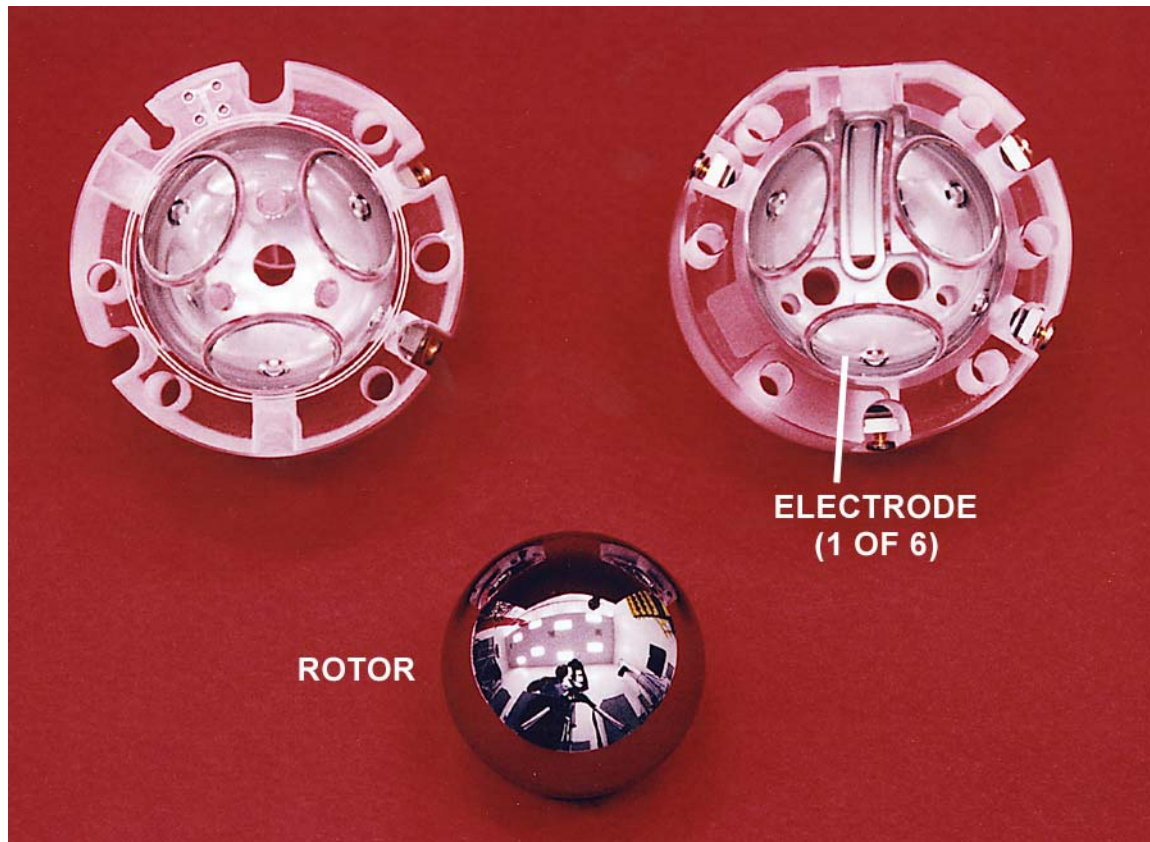


Figure 1. A photograph of the gyroscope rotor and its housing.

The fused quartz gyroscope housing has three orthogonal pairs of circular electrodes which are coated with multilayer Ti-Cu thin films. The requirements for these electrode films are: (1) good adhesion to the fused quartz substrate, (2) good electrical and thermal conductivity, (3) low tensile stress in the film, (4) resistance to arcing damage for an arc energy of less than 3×10^{-4} J. (5) film thickness uniformity of better than 10% over the electrode surface, (6) superconducting transition temperature of less than 1.5 K, and (7) low electron field emission for fields of up to 3×10^7 V·m⁻¹. These requirements ensure the mechanical and electrical integrity of the gyroscope housings over the temperature range from 2 K to 300 K, and voltages range from less than 20 mV up to 2,000 V. The uniformity of the suspension electrode films is required to limit some disturbance torques on the gyroscope rotor. The multilayer Ti-Cu films have been successfully applied to the gyroscope housings, meeting all requirements in 100,000 hours of gyroscope testing on the ground and during the science data collection in Earth orbit for more than one year.

The multilayer Ti-Cu thin film deposition processes applied to gyroscope housings and resulting film characteristics and gyroscope performance are discussed in this paper.

2. Experimental details

All multilayer Ti-Cu thin films were prepared with a magnetron sputtering system. The detailed procedures for the coating technique and the coating of housings have been previously described [5]. Prior to deposition, a housing half or sample substrate is cleaned by scrubbing the fused quartz with urethane foam in MIRCO detergent solution, immersing and rinsing in hot water and deionized water to

remove particles and drying in a vacuum for three hours at about 100°C. The sputtering chamber was evacuated to a base pressure of about 6×10^{-5} Pa using a turbopump with a liquid nitrogen trap. The sputtering pressure was 0.9 Pa at an Ar flow rate of about 22 standard $\text{cm}^3 \cdot \text{min}^{-1}$. The Ti film was deposited using r.f. magnetron sputtering and the thickness was controlled by changing the deposition time. The Cu film was prepared using d.c. magnetron sputtering and the thickness was monitored with an Inficon IC-6000 quartz crystal monitor. Both the copper and the titanium targets were 99.995% pure.

The deposition rates were 0.4 nm/s for Ti and 2.2 nm/s for Cu. Several different sample films were investigated: (1) single layer Cu(1000 nm), (2) bi-layer Ti(100 nm)-Cu (2500 nm), (3) tri-layer Ti(100 nm)-Cu(2500 nm)-Ti(250 nm), and (4) 7-layer Ti(100 nm)-Cu(870 nm)-Ti(50 nm)-Cu(870 nm)-Ti(50 nm)-Cu(870 nm)-Ti(200 nm). The approximate thicknesses of the layers are given in parentheses. The configurations for the multilayer films applied to the gyroscope housings to form the suspension electrodes and the support and spin-up lands are shown in Figure 4. These films were deposited without breaking vacuum between the depositions of successive layers. No substrate heating was added. After deposition, the gyroscope housing was carefully cleaned with a similar procedure that was used for the fused quartz substrate.

3. Multilayer Ti-Cu film characterization

It is desirable to improve the suspension electrode films so they have greater resistance to electrical breakdown, and lower electron-field-emission current to reduce gyroscope rotor electrical charging. In the series of studies, three types of multilayer Ti-Cu films with film thicknesses of about 3 μm were examined. The configurations of these samples are summarized in Table 1. The first Ti layer provides good adhesion to the fused quartz substrate. The intermediate Cu layer provides low electrical resistance and good thermal conductivity. The outer Ti layer provides a high melting point material and improves the electron-field-emission characteristics. Cryogenic magnetic screening tests [6] confirm that multilayer Ti-Cu films are not superconducting and exhibit extremely low magnetic remanence.

Table 1. Layer and total thickness of multilayer Ti-Cu films

Film	Thickness (μm)							Total
	Layer							
	1 st Ti	2 nd Cu	3 rd Ti	4 th Cu	5 th Ti	6 th Cu	7 th Ti	
Bilayer 1A	0.10	2.50						2.60
Trilayer 3B	0.10	2.56	0.20					2.86
Seven layer 7C	0.10	0.79	0.05	0.79	0.05	0.79	0.20	2.77

3.1. Adhesion tests

Tape peel testing was used to verify adhesion. Adhesion failures were observed for the single layer Cu films, indicating that copper films have poor adhesion to the fused quartz substrate. For Ti-Cu, Ti-Cu-Ti and 7-layer Ti-Cu films, a thin Ti layer was coated on the fused quartz substrate, and no adhesion failures were found in room temperature testing and in testing after thermal cycling to 77 K. Tri-layer Ti-Cu-Ti and 7-layer Ti-Cu gyroscope housing electrode films have passed scotch tape adhesion testing

after temperature cycling between 4 K and 400 K. The base Ti layer provides good adhesion to the fused quartz substrate of the gyroscope housing and the copper provides the high electrical conductivity for the electrode.

3.2. Electron field emission

A number of films were studied in order to find a suspension electrode film with a low electron-field-emission enhancement factor. The Ti(100 nm)-Cu(2500 nm) and Ti(100 nm)-Cu(2500 nm)-Ti(250 nm) films were tested with an electron-field-emission test apparatus. A polished rounded tungsten tip was positioned close to the surface of the film using a microstepping servo motor and a capacitance bridge. The electron-field-emission current was measured as a function of the electric field for distances of 25 μm to 50 μm at a pressure of about 5×10^{-6} Pa. Figure 2 shows the electric field required to reach an electron-field-emission current of 2 pA for the two films. It can be seen that the corresponding field for the Ti(100 nm)-Cu(2500 nm)-Ti(250 nm) film is about $10^8 \text{ V}\cdot\text{m}^{-1}$ and is higher than that of the bi-layer Ti-Cu film. Tri-layer Ti-Cu-Ti films have been coated onto fused quartz gyroscope housings. The trilayer Ti-Cu-Ti electrode films exhibit reduced electron field emission, which in turn reduces gyroscope rotor electrical charging. As a result, the Ti-Cu-Ti electrode films have greater resistance to electrical breakdown. Test gyroscopes with tri-layer suspension electrodes have been successfully suspended in their gyroscope housing and spun to about 170 Hz.

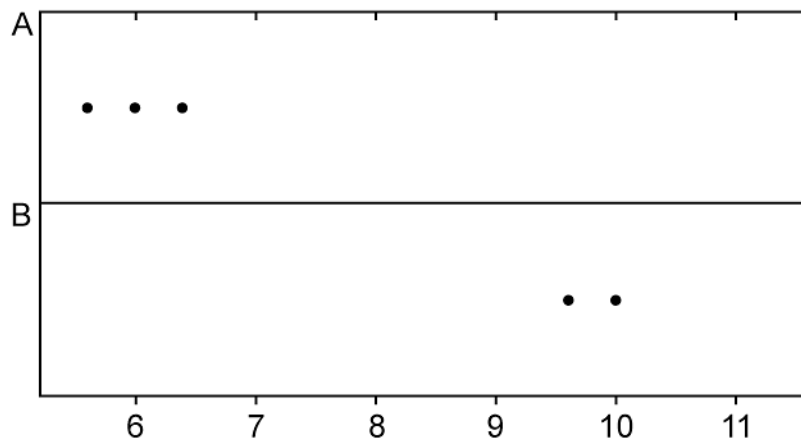


Figure 2. The electric field required for an electron field emission current of 2 pA for two samples: (A) bilayer Ti (100nm) /Cu (2500 nm) film; (B) trilayer Ti (100nm)/Cu (2500 nm)/Ti (250 nm) film.

3.3. Scanning electron microscopy (SEM)

The surface morphology of the two films was examined using scanning electron microscopy (SEM). Figure 3(a) and 3(b) are SEM micrographs of the surfaces of samples 3B and 7C, respectively. The grain sizes are about 0.35 μm for the trilayer film 3B, and about 0.20 μm for the 7-layer sample 7C. The 7-layer films produce smoother surfaces. The surface roughness decreases for thinner intermediate Cu layers. The Ti layers interrupt the copper crystal growth to achieve a smoother surface for the 7-layer Ti-Cu films. The 7-layer Ti-Cu electrode films with their smoother surfaces contribute to reduce electrical charging.

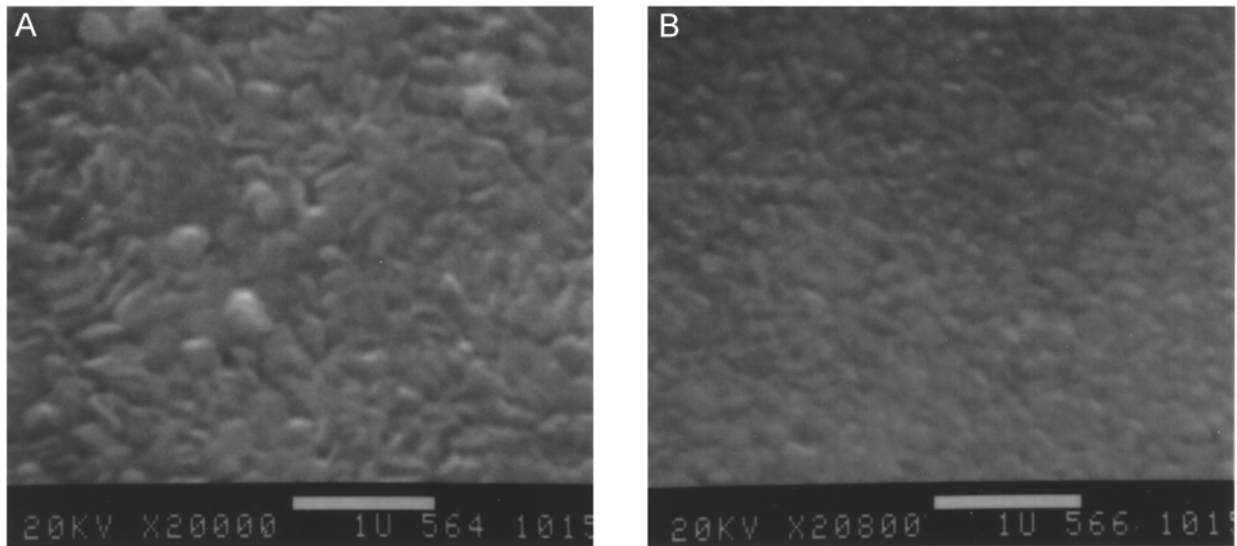


Figure 3. SEM micrographs of the surfaces of samples: (A) trilayer Ti-Cu-Ti film; (B) seven layer Ti-Cu film.

3.4. Resistivity measurement

The resistivity of the samples was measured using a four-point method. Table 2 lists the resistivity data for Cu, Ti-Cu-Ti and 7-layer Ti-Cu films. The resistivity value of the Cu films at room temperature is slightly higher than that of bulk copper ($1.67 \mu\Omega\cdot\text{cm}$). The 7-layer Ti-Cu film has a resistivity similar to that of the Cu film. The total thickness of copper layers is about 85% of the film thickness in the 7-layer Ti-Cu films. The resistivity values of the multilayer films at 4.2 K are below the GP-B requirement of $27 \mu\Omega\cdot\text{m}$. The intermediate Cu layers provide low electrical resistance and good thermal conductivity.

Table 2. Copper and multilayer Ti-Cu film resistivity

Film	Cu	Ti/Cu/Ti	Ti/Cu/Ti/Cu/Ti/Cu/Ti
Film Thickness (μm)	0.9	2.8	2.7
Resistivity ($\mu\Omega\cdot\text{cm}$) at 4.2 K	0.05	0.23	0.14
Resistivity ($\mu\Omega\cdot\text{cm}$) at 280 K	2	3.6	2

4. Multilayer Ti-Cu and Ti films for the flight gyroscope housings

The gyroscope housing incorporates four types of multilayer films inside the housing cavity: electrodes to allow electrostatic suspension, support lands to prevent the rotor from making electrical contact with the electrodes, a spin-up land around the spin-up channel to reduce helium gas leakage out of the gas spin-up channel into the electrode regions during gas spin-up of the gyroscope rotor. Except for the suspension electrodes, the entire interior of the gyroscope housing is coated with a $0.12 \mu\text{m}$ thick Ti layer to minimize the effects of electrostatic charges on the interior surface of the gyroscope housing.

Each feature is deposited independently with titanium masks and it is centered in the deposition flux at the appropriate orientation. The thickness profile of each coated feature is measured with a Talyrond 73 (Rank Taylor Hobson, U.K.) roundness measuring system, which utilizes a contacting stylus mounted on a precision spindle

The 7-layer Ti-Cu films were used for the GP-B gyroscope housing suspension electrodes, and the tri-layer Ti-Cu-Ti films were used for the support and spin-up lands. The configurations of these two multilayer films are illustrated in Figure 4. The thickness uniformity of each suspension electrode and spin-up land is better than 10%. No adhesion failures were observed for the 7-layer suspension electrodes and for the tri-layer Ti-Cu-Ti lands. The first Ti layer provides good adhesion to the fused quartz gyroscope housing, ensuring that copper provides a good interconnection material for gyroscope housings. The 200 nm Ti outer layer reduces electron-field-emission in high electric fields and protects the copper films from corrosion. The four flight gyroscopes were successfully tested on the ground before flight.

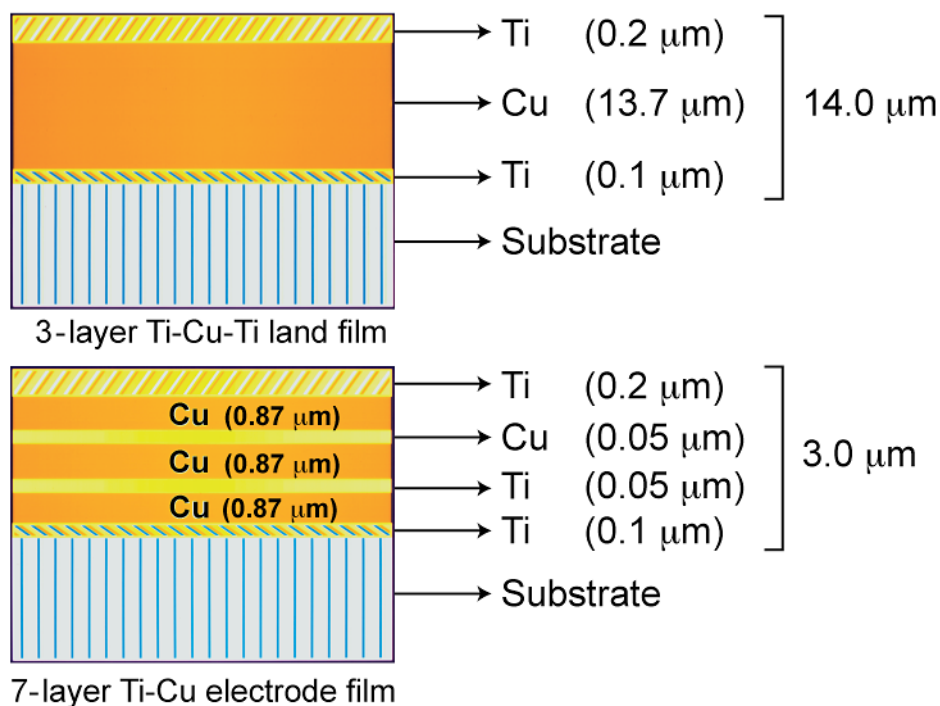


Figure 4. The thickness and layers of seven layer Ti-Cu electrode film and trilayer Ti-Cu-Ti land film.

5. On-orbit performance of the GP-B gyroscopes

GP-B spacecraft has been in orbit for over two years. At the heart of the spacecraft are the four gyroscopes that are the reference for local inertial space in the gravitational field around earth. Each gyroscope supplies the measurement of both the Geodetic and Frame-dragging effects predicted by Einstein's General Relativity. The fused quartz gyroscope housing with its three pairs of suspension thin film electrodes and its support and spin-up lands supports electrostatic suspension, position sensing, helium gas spin-up, and charge management. The gyroscopes are controlled by the gyroscope suspension system which is described by Buchman *et al.* [7]. On-orbit performance of the Gravity Probe B gyroscopes and electrostatic suspension system are described by Bencze [8]. The gyroscope rotor is suspended in the spherical interior of the gyroscope housing with a nominal rotor to suspension-

electrode gap of 32 μm . Six electrodes lying along three perpendicular axes used to both measure the position of the rotor and also provide the electric field necessary to maintain the rotor at a centered position for each of the electrodes. The rotors are electrostatically suspended using the same electrodes. To operate as a gyroscope, the suspended rotor is spun to about (about 75 Hz) using helium gas spin up. The final spin rates of the four gyroscopes are in the range of 60 Hz to 80 Hz. To perform gyroscope spin up, approximately 150 VDC is required on the suspension electrodes to hold the rotor in position when spin-up gas is flowing. The four flight gyroscopes performed well during science data collection for more than one year, which ended on 29 September 2005 when the liquid helium in the dewar was depleted.

6. Conclusions

Multilayer Ti-Cu thin films were applied to the Gravity probe B gyroscope housings. The thin films were deposited by sputtering onto fused quartz gyroscope housings to form the six suspension electrodes and the support and spin-up lands. The 7-layer Ti-Cu films provide good adhesion, low electrical resistivity, good thermal conductivity, and smooth surfaces. The 7-layer Ti-Cu films have been successfully used in the Gravity Probe B gyroscope housing electrodes, meeting all requirements. Multilayer Ti-Cu thin films for the gyroscope housings have met the following requirements: (1) electrode uniformity, (2) the ability to test the gyroscopes on the ground, (3) low gyroscope rotor charging rate, (4) suspension in a variety of conditions, (5) low magnetic remanence, (6) films that are not superconducting above 1.5 K, and (7) the capability to spin up the gyroscopes. The gyroscopes were successfully spun to 170 Hz for more than 100,000 hours testing on ground. The four flight gyroscopes performed well during the science data collection in Earth orbit for more than one year.

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