Available online at www.sciencedirect.com
SciVerse ScienceDirect
Acta Materialia 60 (2012) 3773–3782
Acta MATERIALIA
www.elsevier.com/locate/actamat

The effect of an electric current on the nanoindentation behavior of tin

Guangfeng Zhao, Ming Liu, Fuqian Yang *

Materials Program, Department of Chemical and Materials Engineering, University of Kentucky, Lexington, KY 40506, USA

Received 13 October 2011; received in revised form 22 March 2012; accepted 26 March 2012
Available online 30 April 2012

Abstract

Electrical–thermal–mechanical interactions determine the reliability and performance of microelectromechanical devices and systems. Using the nanoindentation technique the effect of an electric current on the indentation deformation of Sn strips was studied for an indentation load in the range 50–200 μN. During the indentation an electric current density in the range 993.05–4087.89 A cm^{-2} was passed through the Sn strips, which introduced electrical–thermal–mechanical interactions. The experimental results showed that the reduced contact modulus decreased with increasing electric current density. For an electric current density less than 4087.89 A cm^{-2} the decrease in the reduced contact modulus with increasing electric current density was mainly controlled by Joule heating due to an electrothermal interaction. The electrothermal interaction caused surface softening of the Sn strips. A simple relation is proposed to describe the dependence of the reduced contact modulus on the electric current density. The indentation hardness decreased with increasing indentation load, showing a normal indentation size effect. Using the relationship between indentation hardness and indentation depth from strain gradient plasticity theory we curve fitted the experimental data and found that both the indentation hardness at the limit of infinite depth and the characteristic length were dependent on the electric current density. Finite element analysis was performed to analyze the indentation deformation of a two-dimensional tin strip under the simultaneous action of an electric current. The simulation results showed that the contact modulus of tin decreased linearly with the square of the electric current density, qualitatively in accordance with experimental observations for an electric current density $\leqslant 2803.7$ A cm^{-2}.

Keywords: Nanoindentation; Elastic behavior; Hardness

1. Introduction

Tin-based alloys have been extensively used in electronic interconnects to provide electrical and mechanical support in microelectronic devices and systems. In contrast to structural materials, these materials experience thermomechanical deformation due to the passage of an electric current in operating electronic devices. The demand for high speed and improved performance of electronic devices and systems has led to miniaturization of the electronics and a significant increase in electric current intensity. This requires electronic interconnects to carry electric currents of high current density which result in electrical–thermal–mechanical interactions. These electrical–thermal–mechanical interactions present great challenges to understanding the effect of electric currents on the mechanical deformation of electronic interconnects in order to improve the performance and reliability of electronic assemblies and packaging.

The mechanical deformation of materials under the action of an electric current depends on local electrical–thermal–mechanical interactions. Ye et al. [1] used Moiré interferometry to measure the displacement change in a Sn95.5–Ag4–Cu0.5 alloy under the action of an electric current and observed large deformation in solder joints at a high electric current density (10 kA cm^{-2}). Xu et al. [2] found that the electric current-induced back stress together with the electron wind force caused the movement of indentation markers in SnAgCu solder joints. Nah et al. [3] evaluated the shear behavior of flip-chip solder joints before and after the passage of an electric current and

---

* Corresponding author. Fax: +1 8593231929.
E-mail address: fyang0@engr.uky.edu (F. Yang).

1359-6454/$36.00 © 2012 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.actamat.2012.03.049

found that the electric current had a significant effect on their shear failure. The failure mode changed from fracture inside the solder joint before the action of the electric current to interfacial failure on the cathode interface after passage of the electric current. Ren et al. [4] observed that the coupling effect of electric current and tensile stress caused a ductile to brittle transition during tensile testing of a Sn95.5–Ag3.8–Cu0.7 alloy. Kumar et al. [5] found that the passage of an electric current through Sn–3.5Ag solder caused brittle failure of solder joints. Chen and Yang [6–8] studied the effect of a direct electric current on the creep deformation of Pb, Sn, and a Sn60–Pb40 alloy and found that the apparent activation energy for steady-state creep decreased with increasing electric current density. Zhu et al. [9] investigated the effect of current crowding on the stress relaxation of pure tin and found that current stressing accelerated stress relaxation. Currently most studies are focused on the effect of a current on the tensile behavior and creep deformation of Sn-based alloys. There are few studies addressing the effect of an electric current on the local mechanical deformation of Sn and Sn alloys, which determines the structural durability of electronic interconnects.

Nanoindentation is a localized testing technique which has been used to characterize the reduced contact modulus and indentation hardness of small volumes of materials and has provided numerous insights into the fundamental mechanisms controlling localized deformation of materials. Few studies have examined the effect of electrical–thermal–mechanical interactions on the indentation behavior of materials. In this work we investigate the indentation deformation of Sn strips when there is an electric current passing through the strips. The effect of the electric current density on Joule heating and the reduced contact modulus is examined. The dependence of indentation hardness on electric current density is also discussed.

2. Electrothermal analysis

Consider a conducting thin film deposited on an insulated substrate. The film thickness t is much smaller than the film length L, and the temperature variation in the thickness direction is expected to be negligible. Thus a one-dimensional electrothermal analysis is adopted. For a d.c. electric current passing through the specimen the steady-state thermal conduction in the film can be described by the following partial differential equation:

$$\frac{d}{dx}\left(kA\frac{dT}{dx}\right)+\frac{\rho_e I^2}{A}-h_c c(T-T_\infty)=0 \tag{1}$$

where T is the local temperature in the strip, k is the specific heat, ρ_e is the electric resistivity, I is the electric current intensity passing through the strip, h_c is the heat transfer coefficient, A is the cross-sectional area of the strip, c is the summation of the area of the top and side surfaces per unit length, and T_∞ is the temperature of the environment (i.e. the temperature suitably far from the surface). The second term in Eq. (1) represents the heat released by Joule heating, and the third term is the heat loss through the top and side surfaces.

The boundary conditions at the ends of the strip are

$$T=T_0 \quad \text{at} \quad x=\pm L/2 \tag{2}$$

where T_0 is the temperature at the ends of the strip. We assume that k, ρ_e, and h_c are independent of T. The solution of Eq. (1) is

$$T=\left(T_0-T_\infty-\frac{\rho_e I^2}{Ach_c}\right)\frac{\cosh\omega x}{\cosh(\omega L/2)}+T_\infty+\frac{\rho_e I^2}{Ach_c} \tag{3}$$

with $\omega^2=ch_c/kA$. At the center of the strip the temperature rise reaches a maximum as

$$T_{\max}=\left(T_0-T_\infty-\frac{\rho_e I^2}{Ach_c}\right)\frac{1}{\cosh(\omega L/2)}+T_\infty+\frac{\rho_e I^2}{Ach_c} \tag{4}$$

The temperature rise is a linear function of $1/\cosh(\omega L/2)$, which suggests that the longer the strip is the smaller the spatial gradient of local temperature. For $T_0=T_\infty$ Eq. (3) gives

$$T-T_\infty=\frac{\rho_e I^2}{Ach_c}\left(1-\frac{\cosh\omega x}{\cosh(\omega L/2)}\right) \tag{5}$$

The temperature rise is proportional to the electric current intensity (electric current density).

3. Experimental

The pure tin bars used in this study were obtained from McMaster-Carr (Chicago, IL). Tin blocks were machined from the tin bars and then rolled into strips 0.3 mm thick which were cut into thin strips of ~3–4 mm in width and ~10 cm in length. The thin strips were then heat treated in air at 347 K for 30 min to release the residual stresses created by machining and rolling and to obtain a homogeneous microstructure before being attached to the surface of a glass slide. The average grain size was ~60 μm. A small tensile force was applied to the strips during sample mounting to avoid possible slipping of the Sn strips on the surface of the glass slide. Tensile force and mechanical pressing at the contact ends between the strip and the glass slide resulted in intimate contact between them, which prevented possible indentation-induced sliding of the strip. The Sn strips were then mechanically ground and polished parallel to the longitudinal direction, and the cross-sectional areas of the polished samples were in the range 1.96×10^{-3}–2.29×10^{-3} cm^2. Using current control a direct electric current was passed through the strips before performing the indentation test and a constant electric current density was maintained during the indentation test. The electric current densities were in the range 993.1–4087.9 A cm^{-2}. During passage of the electric current through the Sn strips the surface temperature of the strips was measured using a thermocouple.