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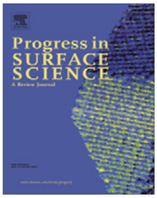

Review

# Growth of whiskers from Sn surfaces: Driving forces and growth mechanisms

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ABSTRACT

Sn whiskers are thin filaments that grow spontaneously out of the surface of coatings on Cu and have become a critical reliability problem in Pb-free electronics. In this review, we focus on what creates the driving force for whiskers (or more rounded "hillocks"), and what determines where on the surface they will form. Experimental studies are reviewed that quantify the relationship between the Cu–Sn intermetallic (IMC) formation, stress in the layer and whisker/hillock density. Measurements of the mechanical properties show how stress relaxation in the Sn layer is intimately related to how much stress develops due to the IMC formation. Real-time scanning electron microscope (SEM)/focused ion beam (FIB) studies are described that illustrate the whisker/hillock growth process in detail. Whiskers are found to grow out of a single grain on the surface with little lateral growth while hillock growth is accompanied by extensive grain growth and crystallite rotation. Electron-backscattering detection (EBSD) shows the grain structure around where the whiskers/hillocks form, indicating that whiskers can grow out of pre-existing grains and do not require the nucleation of new grains. This has led to a picture in which stress builds up due to IMC growth and causes whiskers/hillocks to form at "weak grains", i.e., grains that have a stress relaxation mechanism that becomes active at a lower stress than its neighbors. FEA (finite element analysis) calculations are used to simulate the evolving stress and whisker growth for several different mechanisms that may lead to "weak" grains.

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## 1. Introduction

Electrodeposited Sn-based coatings are used extensively in the electronics industry to protect conductors, reduce oxidation and enhance solderability. However, these coatings are susceptible to the formation of Sn whiskers (i.e., thin filaments that grow spontaneously out of the surface of the Sn layer) that can lead to short circuits and system failures [1] Until recently, Pb has been used as an alloying element to suppress whisker formation. The adoption of environmental regulations (RoHS [2]) that mandate the elimination of Pb in manufacturing has led to the re-emergence of whiskering as a critical reliability issue in Pb-free electronics.

Effective mitigation of whiskering requires an understanding of how and why they form. Yet despite intense interest in whisker formation, the fundamental mechanisms controlling their growth are still not understood. Part of the difficulty is that multiple materials processes interact to create the whiskers (e.g., interdiffusion, phase transformation, stress generation and relaxation, etc.) so that it is not easy to identify the underlying mechanisms. Moreover, many processing variables (film thickness [3–8], grain size [4,5,7,9], plating conditions [3,10–12], microstructure [7,13–16] and composition [7,13,17,18]) have been shown to play a role which makes it difficult to compare the results of different studies done under different conditions. Therefore, systematic experiments in conjunction with modeling are need to understand how and why they form.

In this review, we discuss recent work focused around two questions central to understanding whisker formation: what is the driving force that leads to whisker formation (and also more rounded "hillocks") and why do they start to form at particular sites on the surface. In each case, we review different mechanisms that have been proposed and describe experimental studies that either support or do not support their role in whisker formation. We also describe FEA simulations that enable us to understand how different processes (IMC formation, plasticity, grain boundary diffusion, etc.) contribute to the evolution of stress in the layer and how the presence of a "weak" grain can lead to the growth of a whisker out of the surface. In the final section, we discuss the implications of these studies for suppressing whiskers, e.g., by enhancing stress relaxation in the layer or reducing the formation of IMC.

## 2. Background

Whiskers were originally observed on Sn surfaces over 50 years ago [19,20] and have been the subject of extensive study [21]. It was discovered that their growth could be suppressed by the addition of Pb [22] so alloy coatings of Sn–Pb have been used in many commercial applications. Nevertheless, whiskers have been implicated in over $1B of losses [23], many of which are documented on the NASA whisker web-site [1]. Failures include the crash of the Hughes Galaxy satellite, recall of medical pace-

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