Whisker Mitigation Strategies for Pb-Free Electronics

M.A. Ashworth and G.D. Wilcox

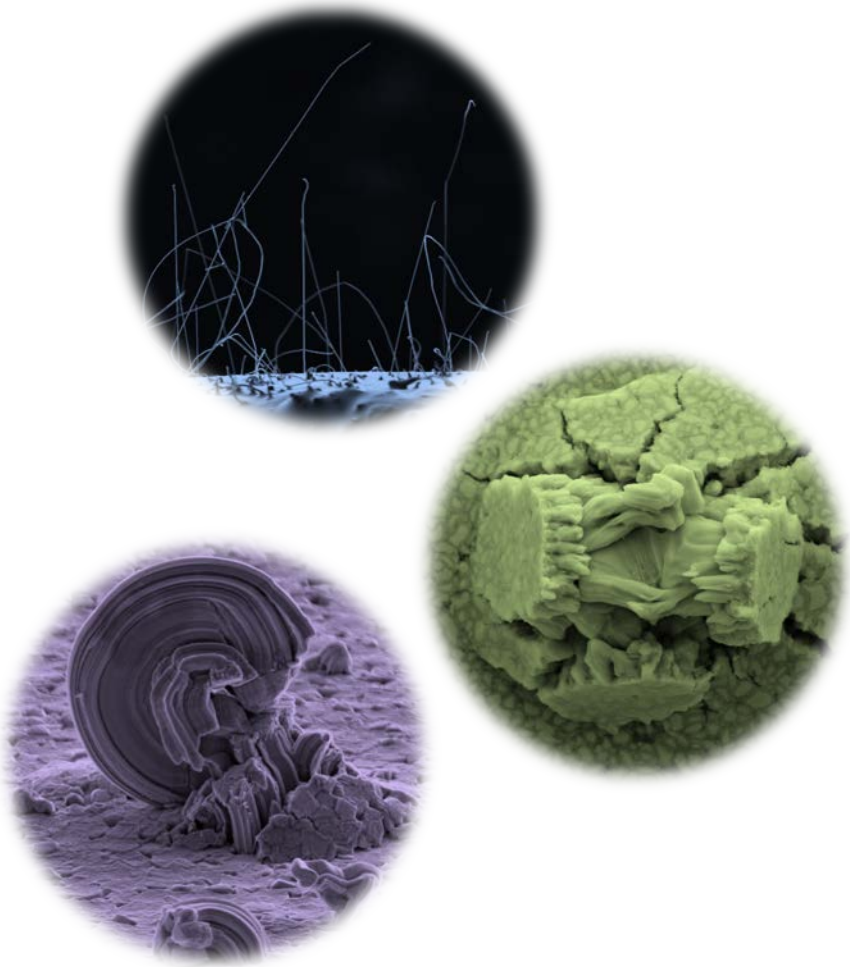
SMART Group

Advances in Electronics Assembly Technology Seminar

16th June 2015

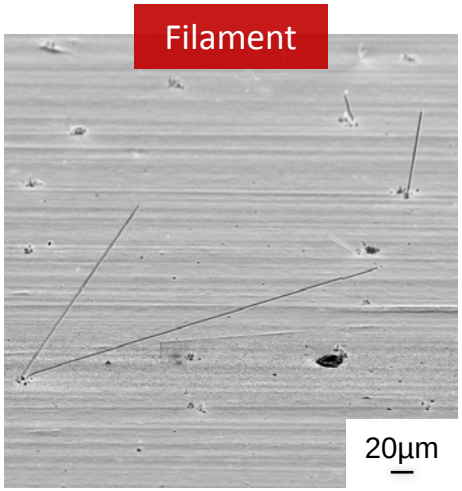
Outline of presentation

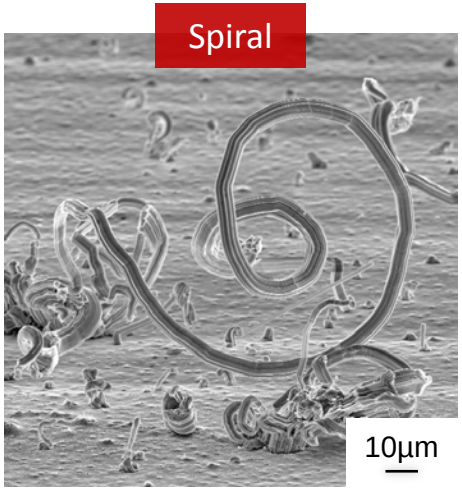
- Background on tin whiskers
- Introduction to WHISKERMIT
- Tin deposits on Cu and brass
- Electrochemical oxidation
- Conformal coatings
- Summary

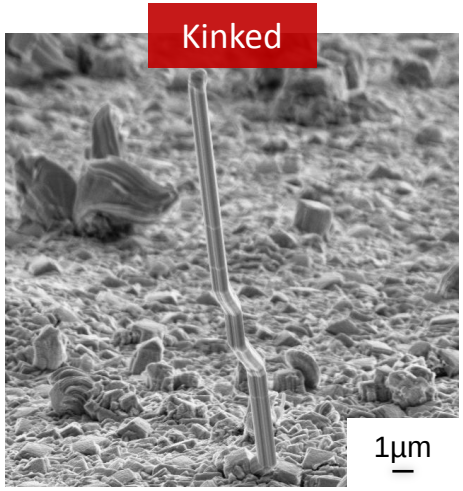


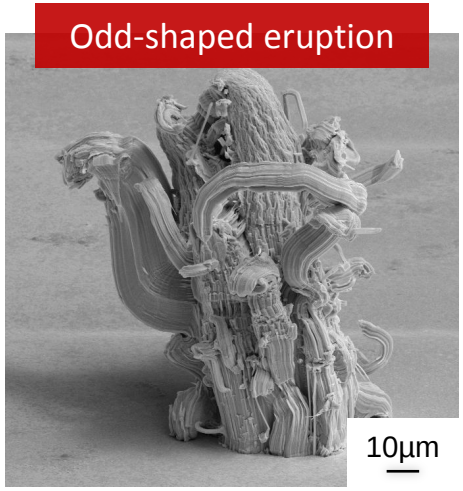
Background – tin whiskers

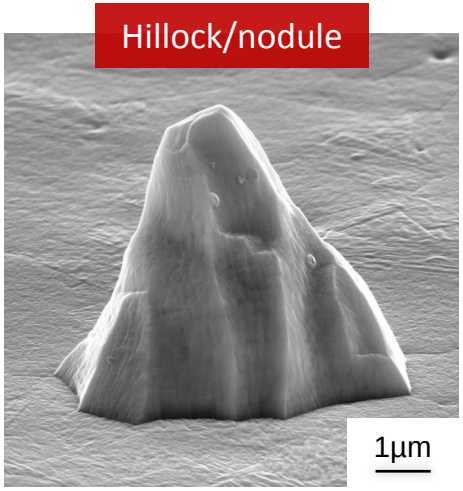
- Crystalline growths from a metal surface (e.g. Sn, Zn and Cd)
- Uncertain incubation period before growth
- A few micrometres in diameter and up to several millimetres in length
- Various growth morphologies possible
- Whisker related problems increasing due to environmental legislation, device miniaturisation, lower voltages and harsher environments











Loughborough University

Documented electronic failures due to tin whiskers

NASA: "More than 50 Electronic Failures due to Whisker Growth from 1946-2006"

Galaxy satellite

Military failures

Heart pacemaker recall

Nuclear power plant

Documented Incidents: Only 10% of Failures known to NASA

Images: www.google.co.uk [Accessed June 2014].

L. Panashchenko, "The Art of Metal Whisker Appreciation: A Practical Guide for Electronics Professionals", NASA Goddard, 2012.

Loughborough University

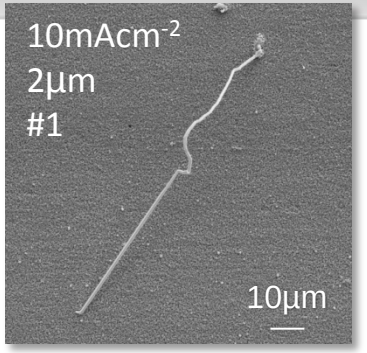
Tin whisker research at Loughborough University

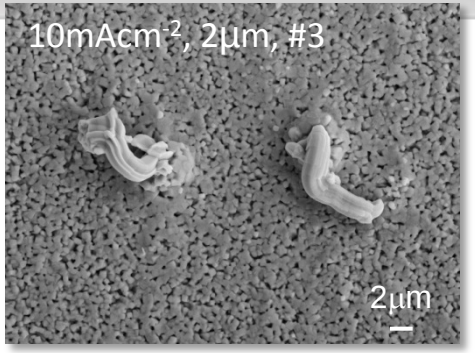
WHISKERMIT

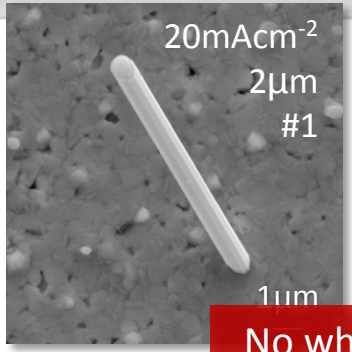
- **Process optimisation (commercial bright tin)**
  - Deposition current density
  - Deposit thickness
  - Pulse plating
  - Incorporation of particulates
- **In-service mitigation strategies**
  - Conformal coating
- **Electrochemical oxidation to mitigate whisker growth**

Loughborough University

Effect of process variables: Sn deposits on Cu



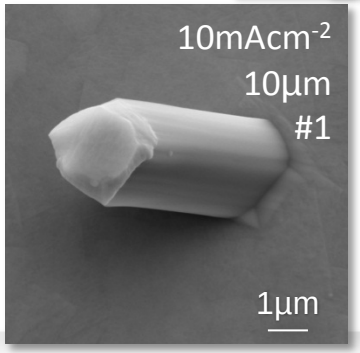


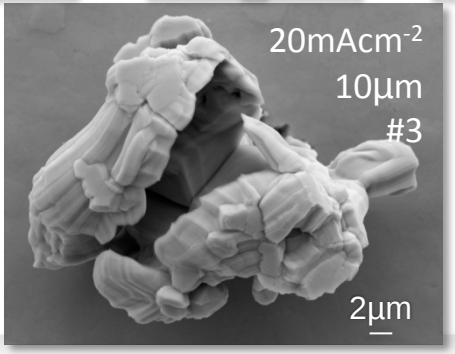


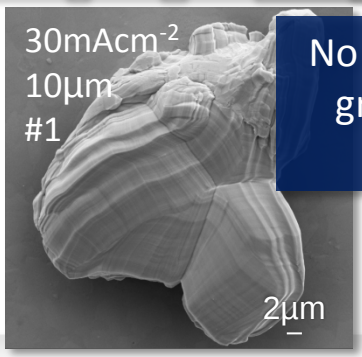
Deposit thickness	10 mA cm^{-2}			20 mA cm^{-2}			30 mA cm^{-2}			40
	#1	#2	#3^{HT}	#1	#2	#3^{HT}	#1	#2	#3^{HT}	#1
2 µm	X		X	X			X			
5 µm			X				X			
10 µm	X					X	X			

No whisker growth from any sample electroplated at 40 mA cm^{-2}

No whisker growth observed from 'batch 2' samples







No increase in whisker growth for samples stored in oven

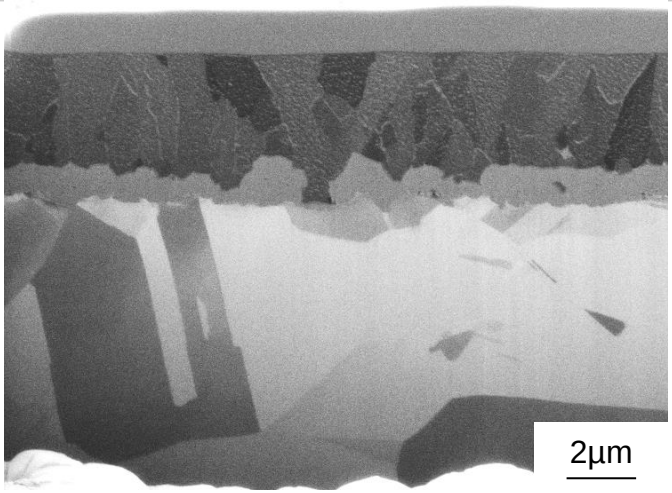
~ 2 years after deposition

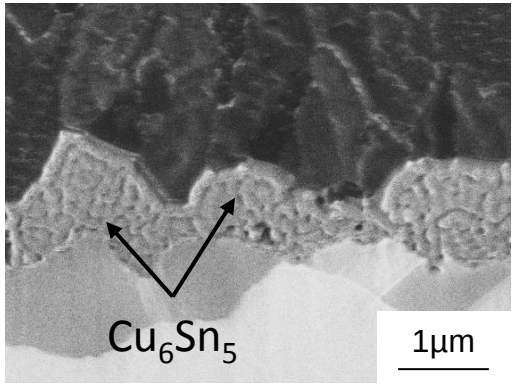
Loughborough University

Effect of elevated temperature on intermetallic formation

5 µm tin
20 mAcm^{-2}

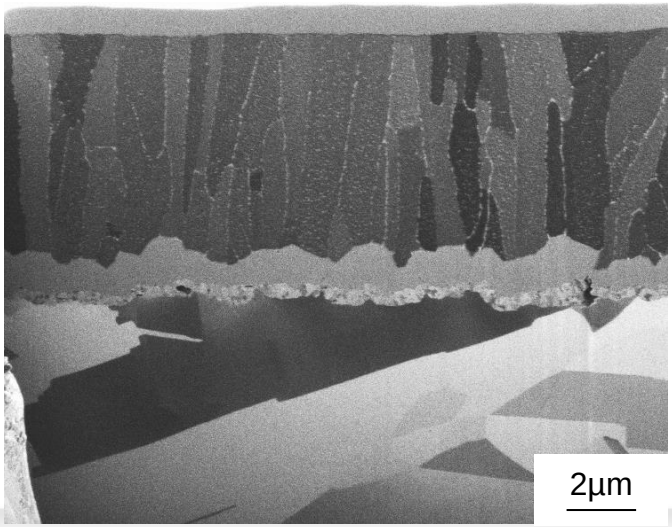
2 years room temperature storage

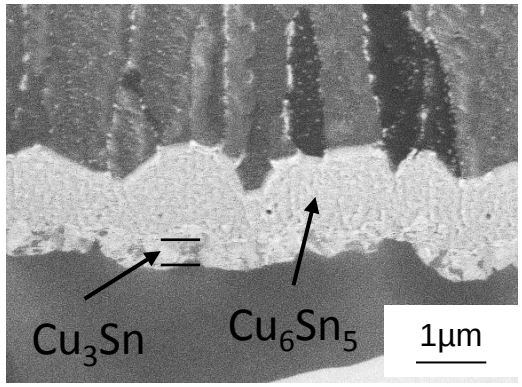




10 µm tin
20 mA cm^{-2}

2 years storage includes 5000 hours at 55°C/85% RH



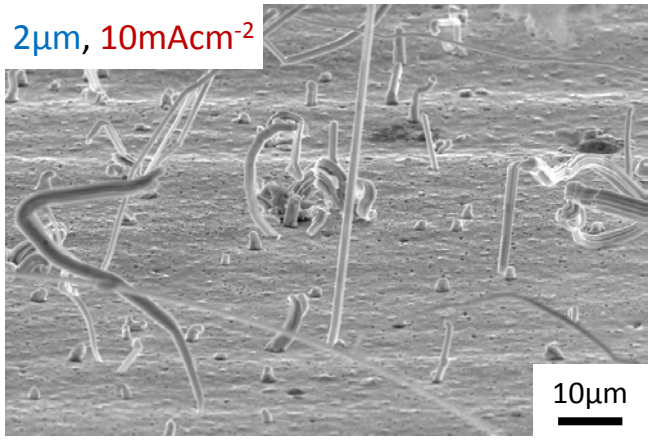


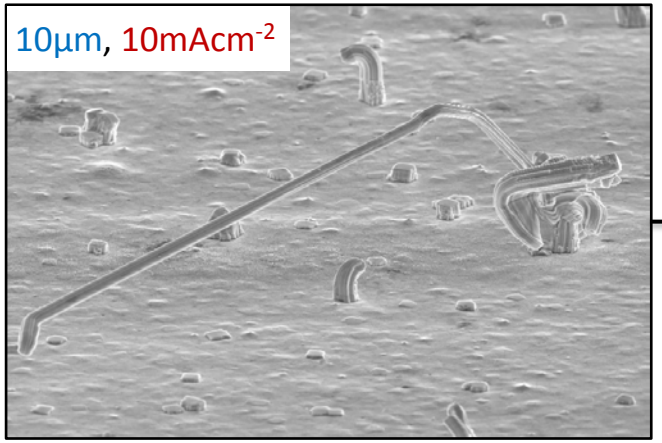
- Cu_3Sn layer develops during storage at 55°C
- IMC layer becomes more planar
- No acceleration in whisker growth observed

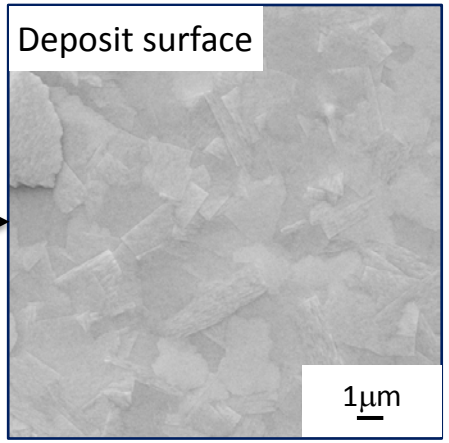
FIB analysis ~ 2 years after tin deposition

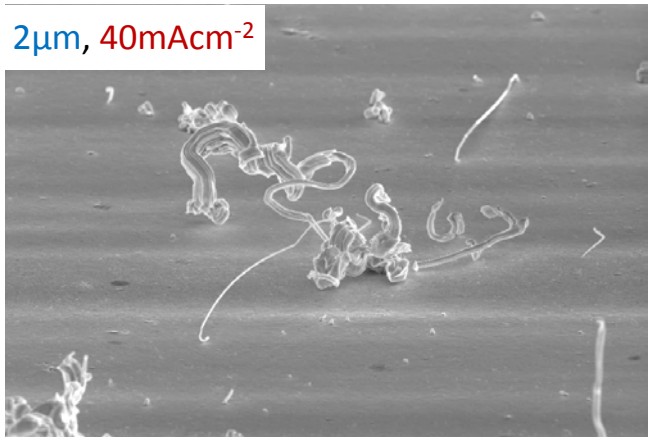
Loughborough University

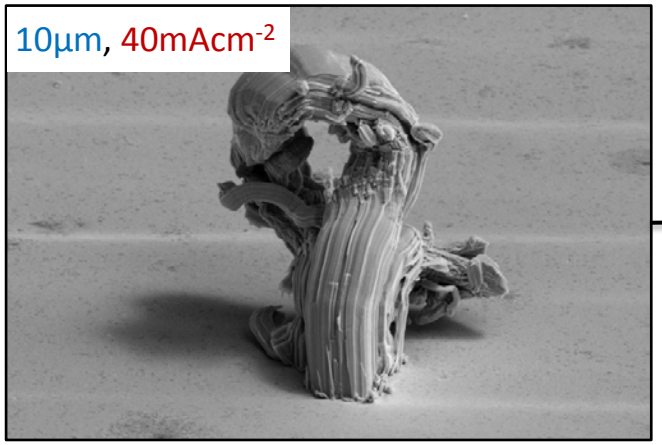
Effect of process variables: Sn deposits on brass

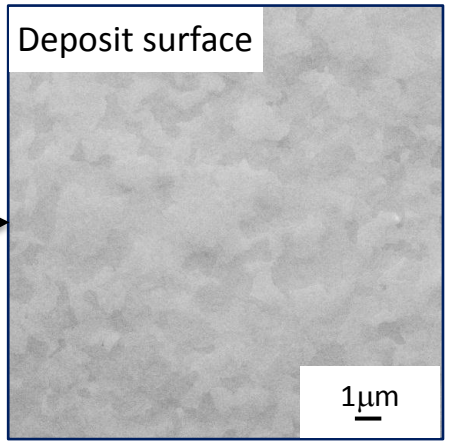












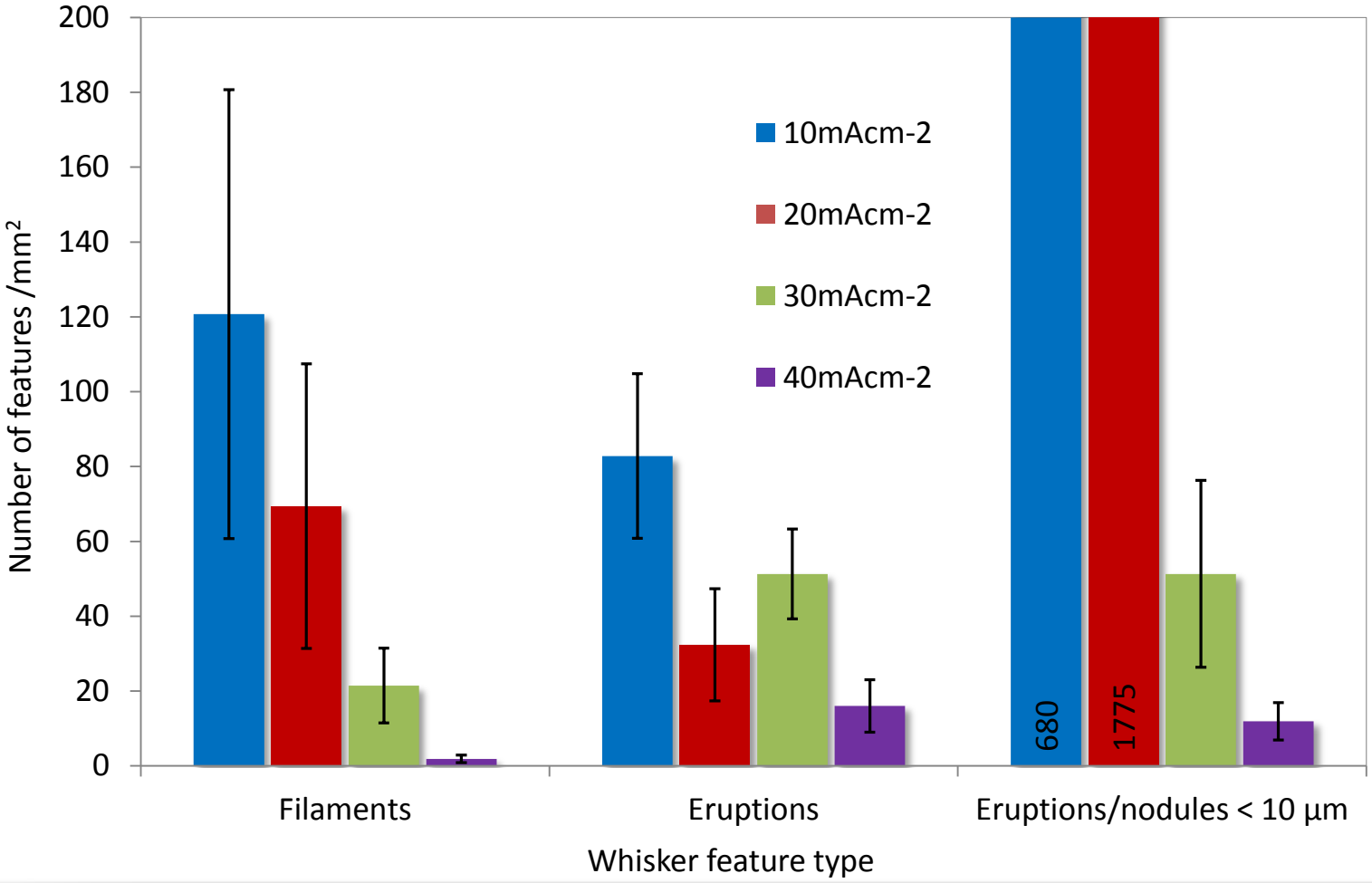
Increased deposition current density

Increased deposit thickness

29 months after deposition

Loughborough University

Effect of deposition current density on whisker growth



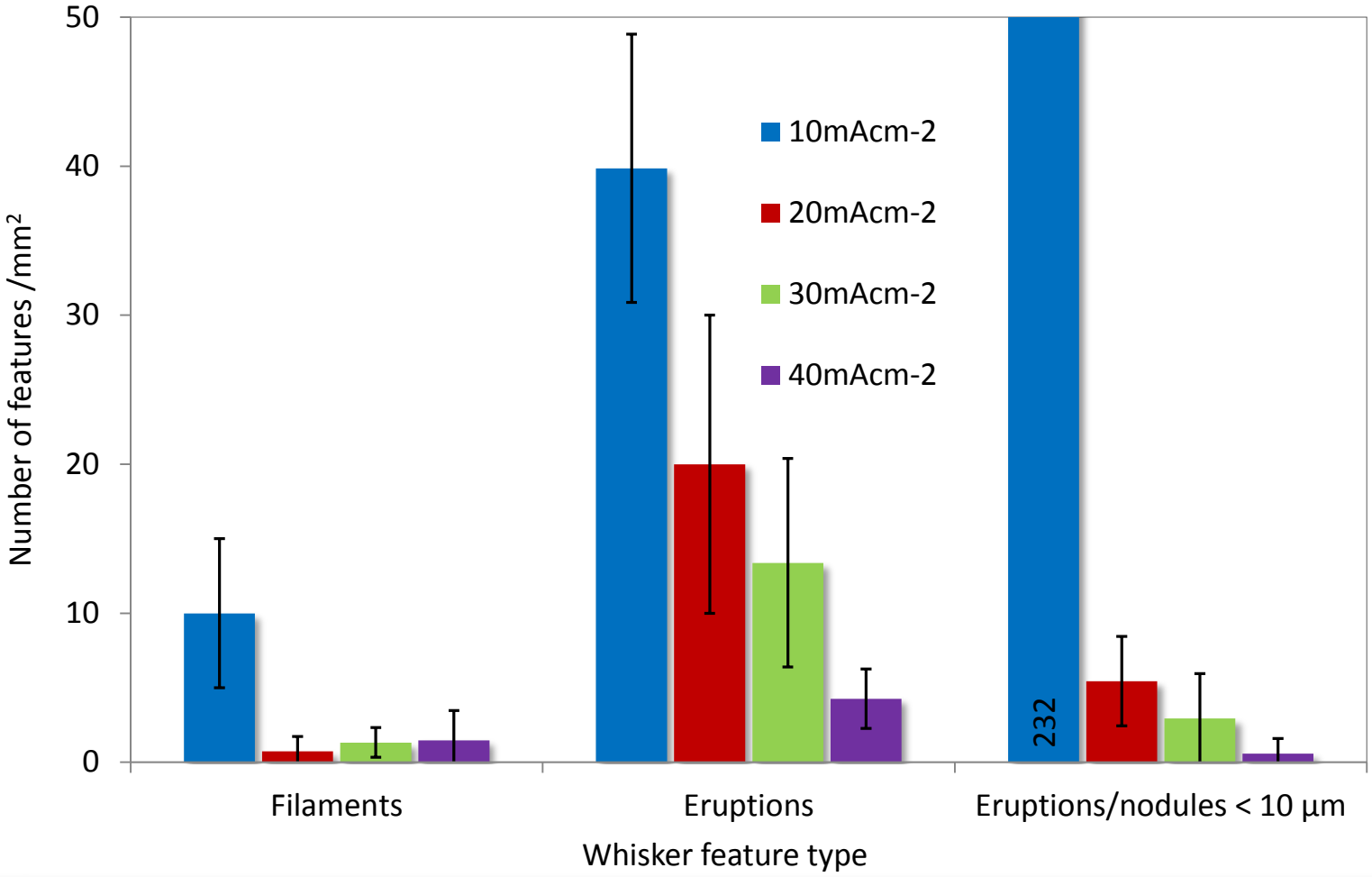
Evaluation of whisker density for **2µm** tin deposits on brass

Analysis approx. 33 months after tin deposition

Storage at room temperature

Loughborough University

Effect of deposition current density on whisker growth



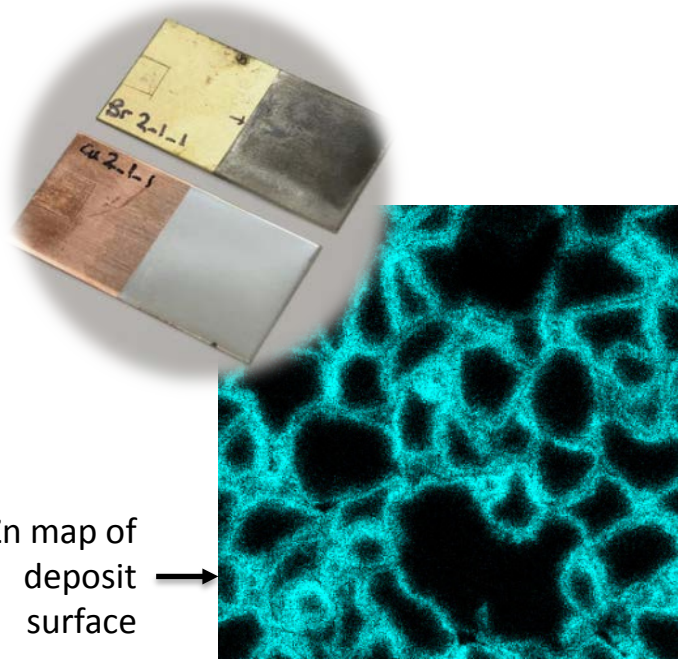
Evaluation of whisker density for **10µm** tin deposits on brass

Analysis approx. 33 months after tin deposition

Storage at room temperature

Loughborough University

Sn deposits on brass: whisker mechanism

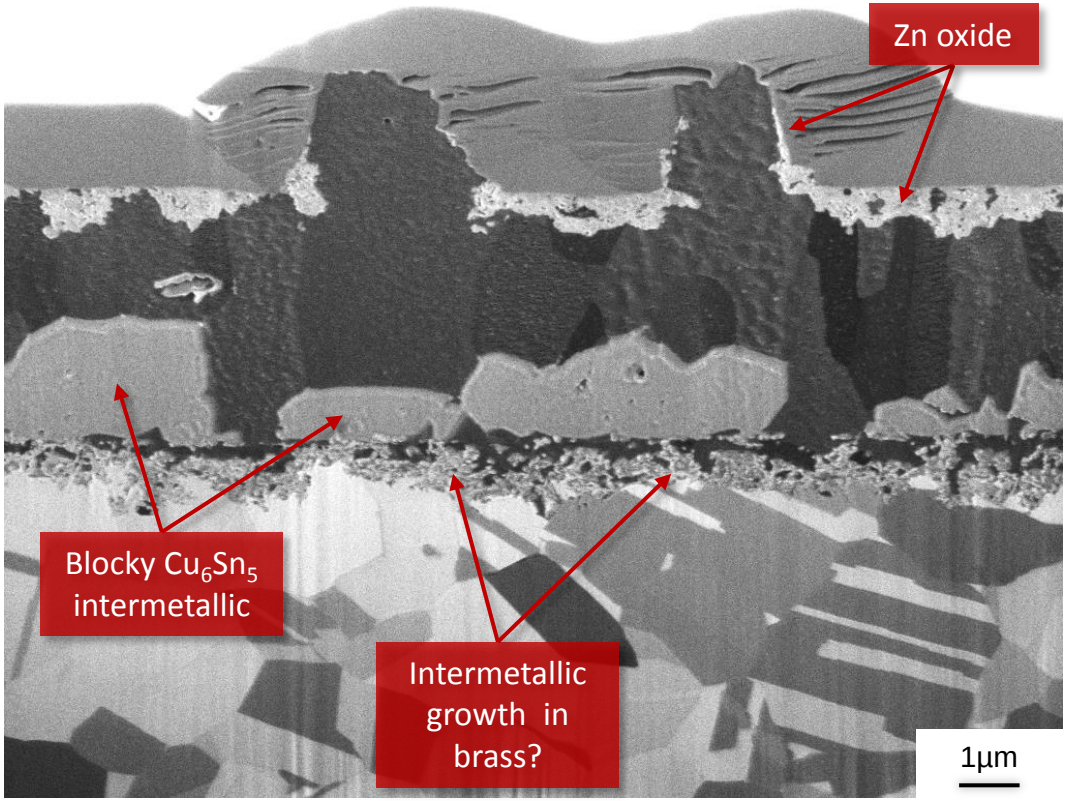


Zn map of deposit surface →

For tin deposits on brass, **whisker growth is primarily driven by zinc oxide formation** at the deposit surface rather than intermetallic growth at the Sn-brass interface

5 µm tin deposit on brass, electroplated at **10 mAcm^{-2}**

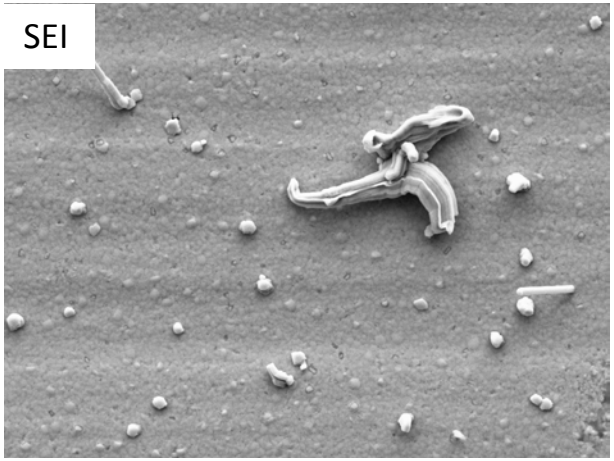
FIB analysis ~29 months after tin deposition

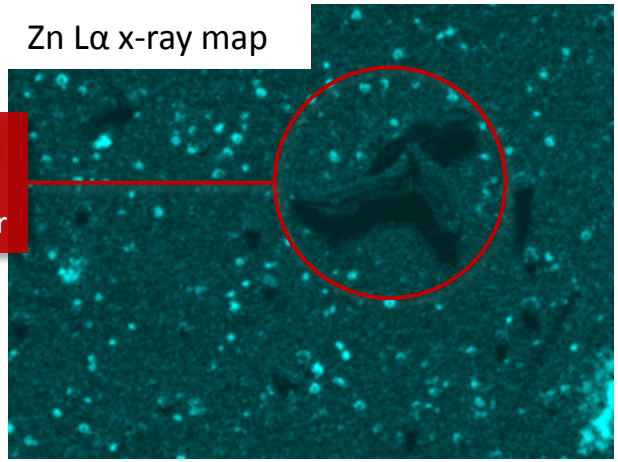


Loughborough University

Tin deposit on brass: Zn present in tin whisker?

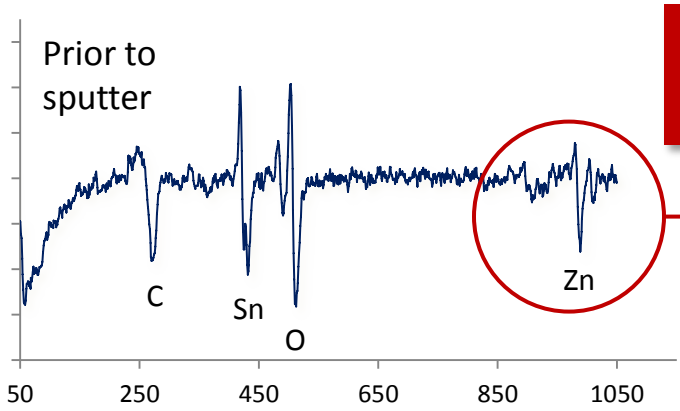
'Bulk' analysis: **SEM/EDX mapping**



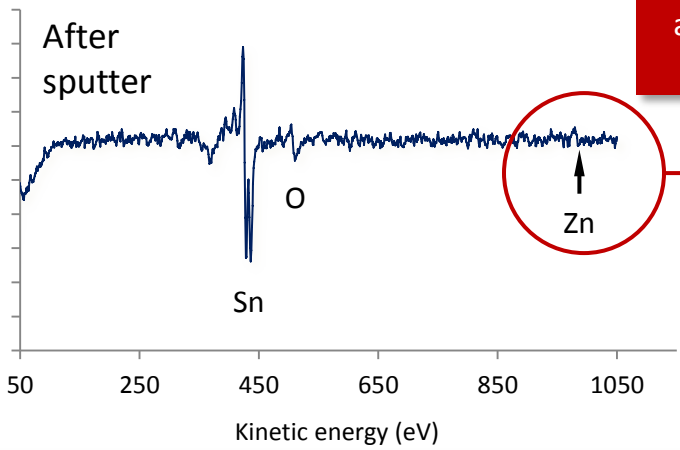


No enriched Zn signal from whisker

Surface analysis: **Auger electron spectroscopy**



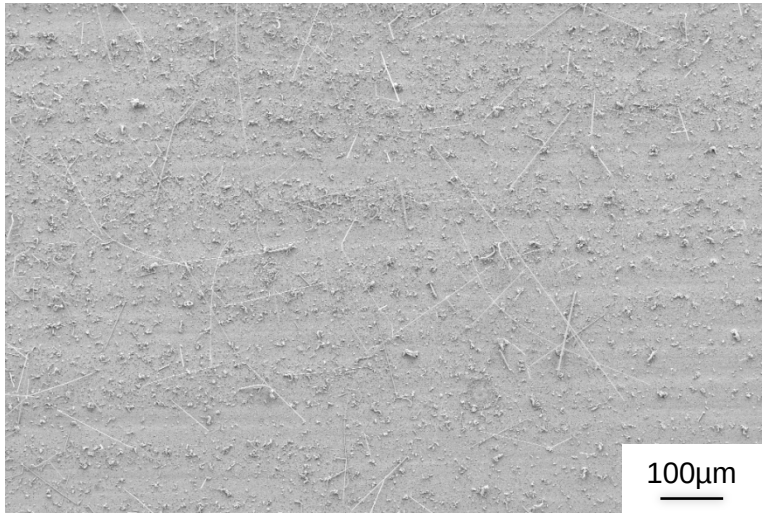
Zn present on whisker surface

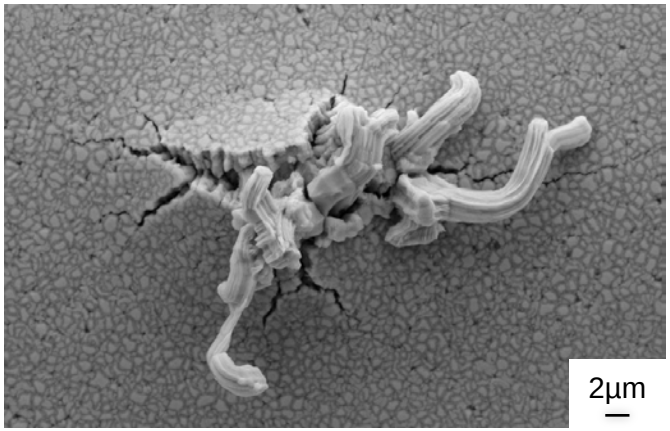


Zn absent after oxide removed

Loughborough University

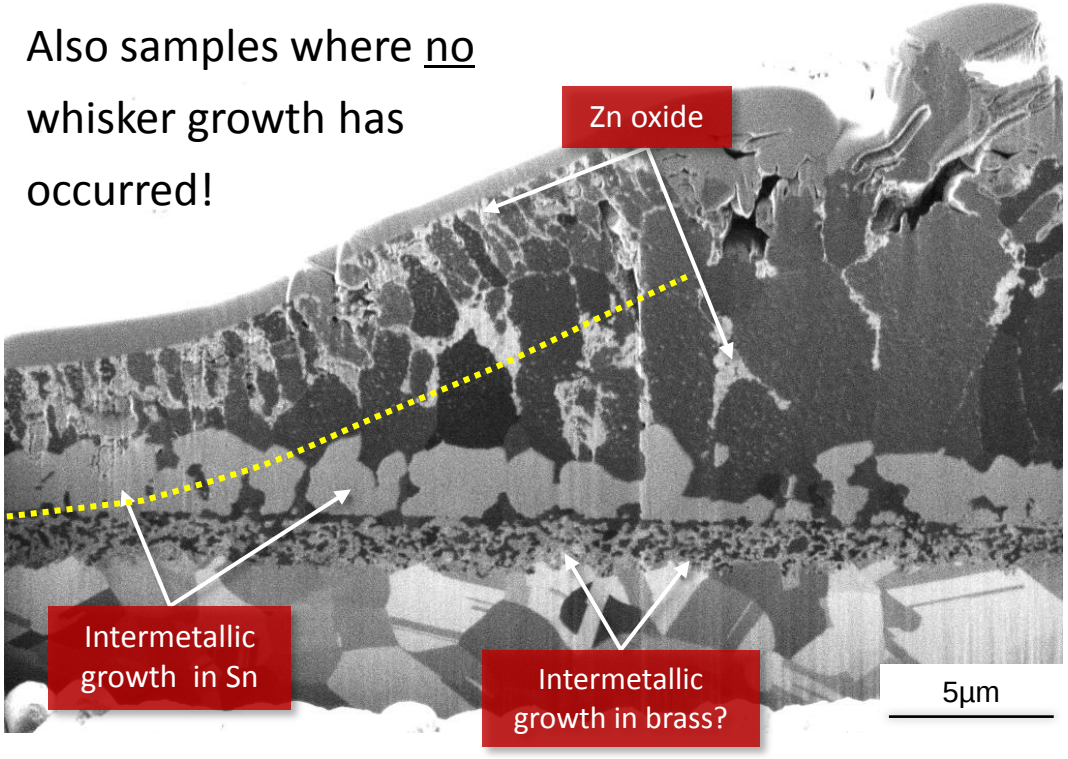
Sn deposit on brass: effect of elevated temperature





Exposure of Sn deposits on brass generally results in a considerable increase in whisker growth

Also samples where no whisker growth has occurred!



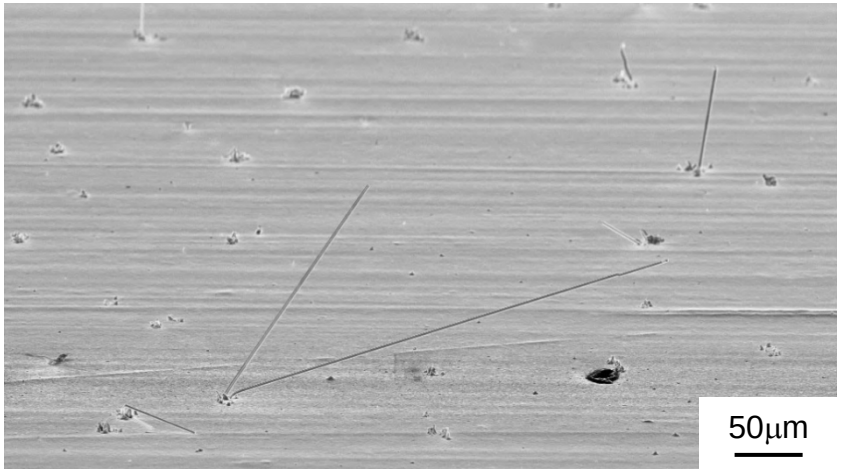
Loughborough University

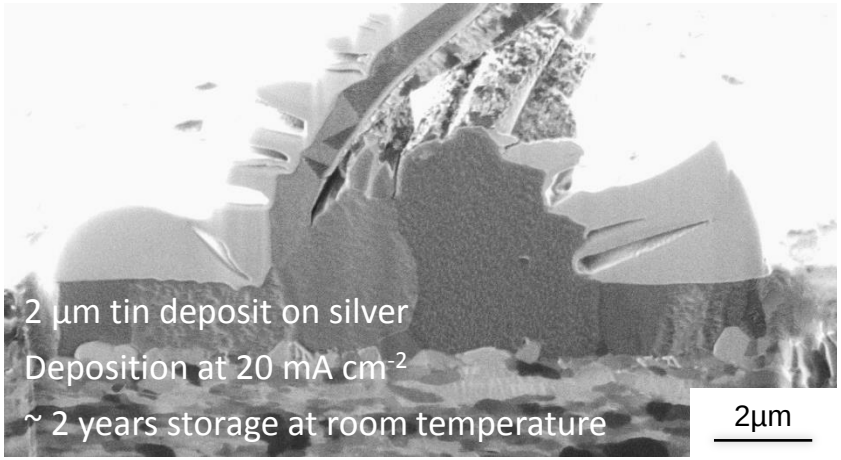
Effect of electroplating parameters

- For both Sn deposits on Cu and Sn deposits on brass, whisker growth is reduced at higher deposition current densities and increased deposit thicknesses
- Current results only applicable for the specific Sn electroplating bath under investigation
- Significant variation in whisker growth may be observed on nominally identical samples
- Although whisker growth is strongly influenced by electroplating parameters, their control cannot be relied upon to successfully mitigate whisker growth ➔ additional control measures are required

Whisker growth for tin deposition on silver

- Ag has been considered as a potential underlayer material to mitigate whisker growth for tin deposits on copper
- Sn deposits on silver sheet whisker much more rapidly than equivalent deposits on copper
- Recent results have also demonstrated increased whisker growth for Sn deposits on Cu with an electroplated Ag barrier layer
- According to Crandall [1]: *"Sn on Ag is a remarkable whisker producer!"* and *"holds our internal lab record for prodigious whisker growth"*





[1] E. R. Crandall, Factors Governing Tin Whisker Growth, PhD thesis, Auburn University, 2012

Loughborough University

The role of the surface oxide in whisker growth

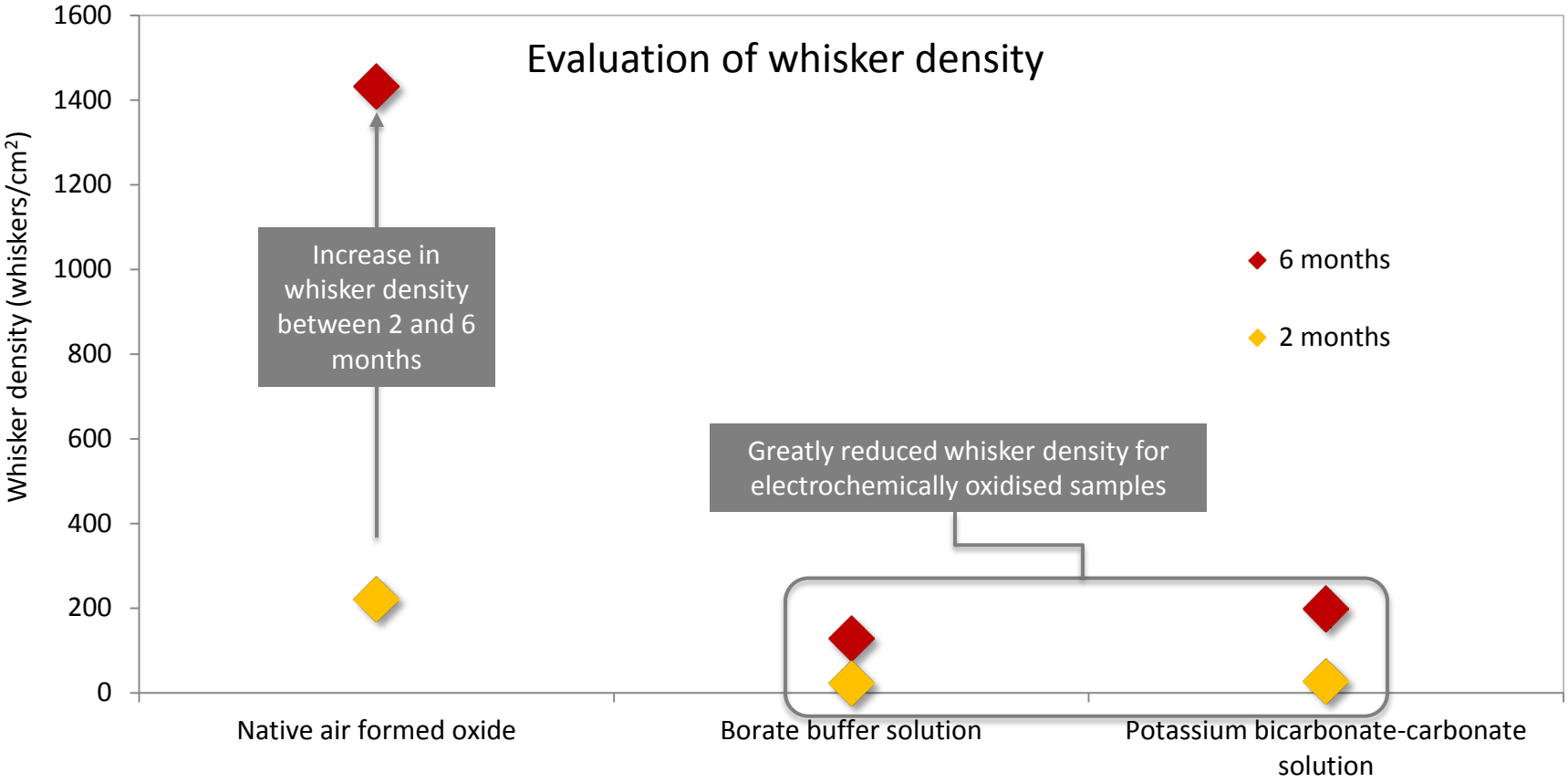
- In 1994, Tu proposed his **“cracked oxide theory”** [1]
  - whisker growth occurs at certain weak spots on the surface where the oxide has been broken
  - In the absence of an oxide no whisker growth would occur

- Later adding [2] …
  - “if the surface oxide is very thick, it will physically block the growth of any hillocks and whiskers”
- *Can we mitigate whisker growth by increasing the thickness of the surface oxide??*

[1] *Physical Review B 49, 2030, 1994*

[2] *Proceedings of the IEEE Electronic Components and Technology Conference, 2002 p1194–1200*

SnCu deposits on Cu: Electrochemical oxidation at 1.2V



2 µm Sn-Cu on Cu deposited at **10 mAcm^{-2}**

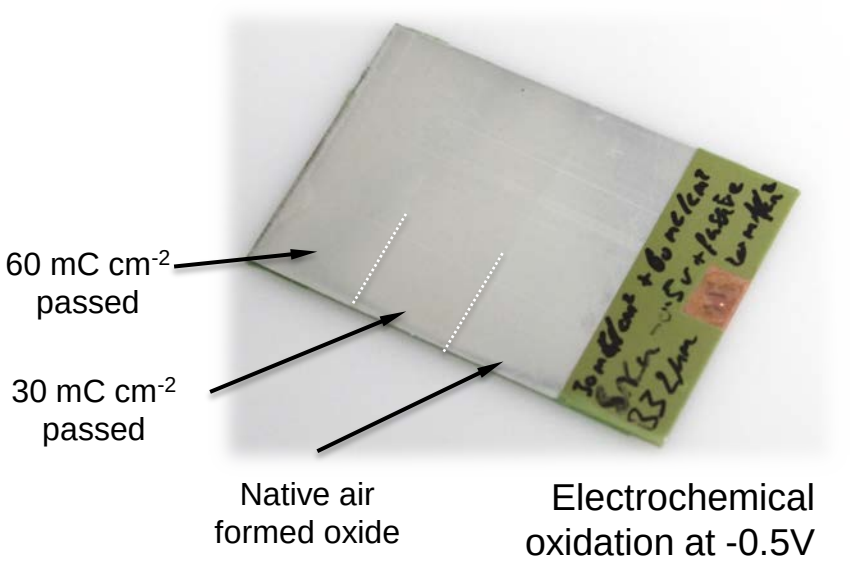
Loughborough University

Test coupons to investigate whisker growth

- To more fully investigate the effect of oxidation potential samples have been electrochemically oxidised in a potassium carbonate-bicarbonate bath at -0.66V, -0.5 V, -0.4V, 0 V and 1.2 V (all vs. SCE).

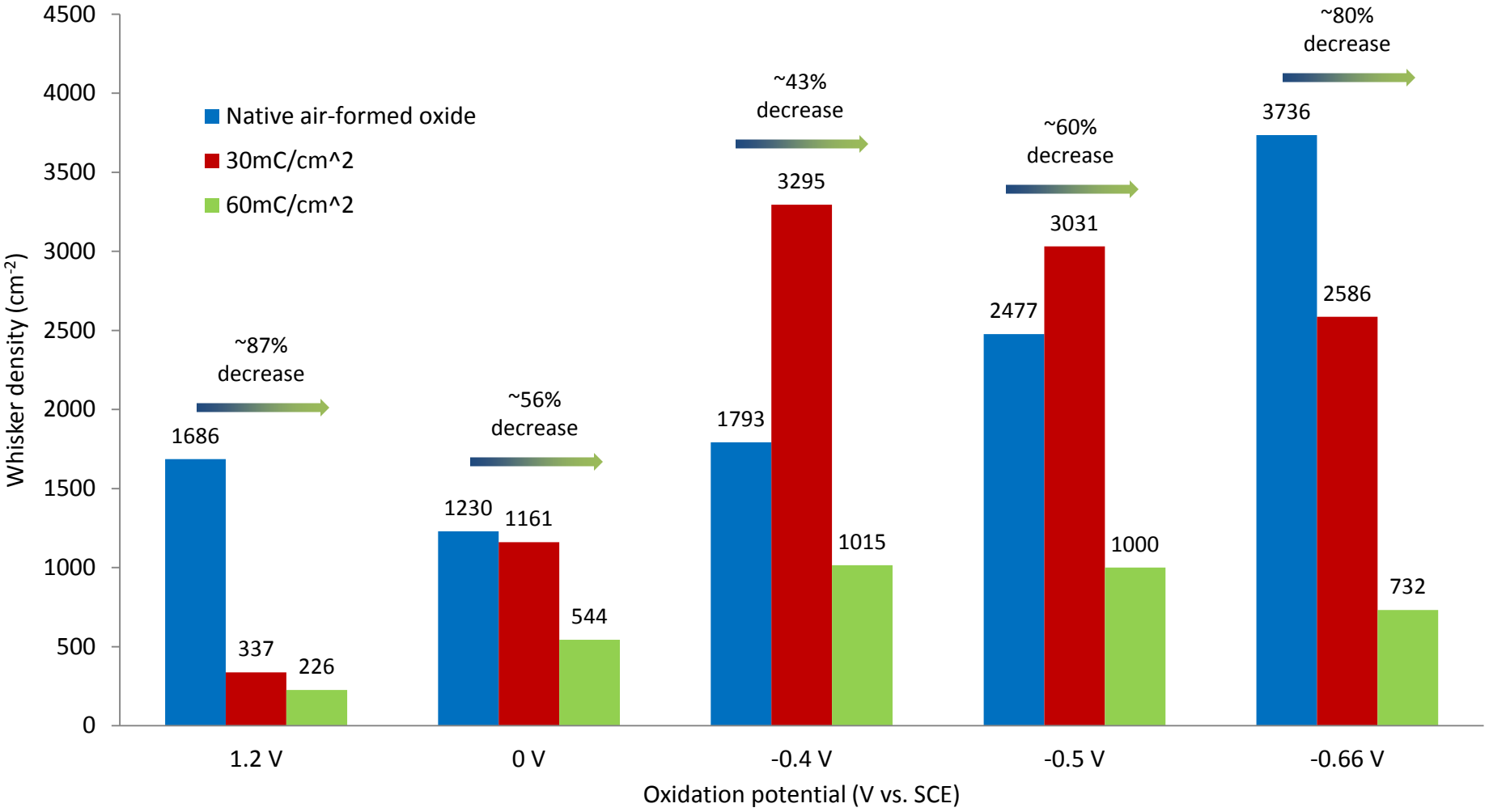
- Regions with both 30 and 60 mC cm^{-2} charge passed

- Whisker growth evaluated using optical microscopy after ~ 2 months storage at room temperature



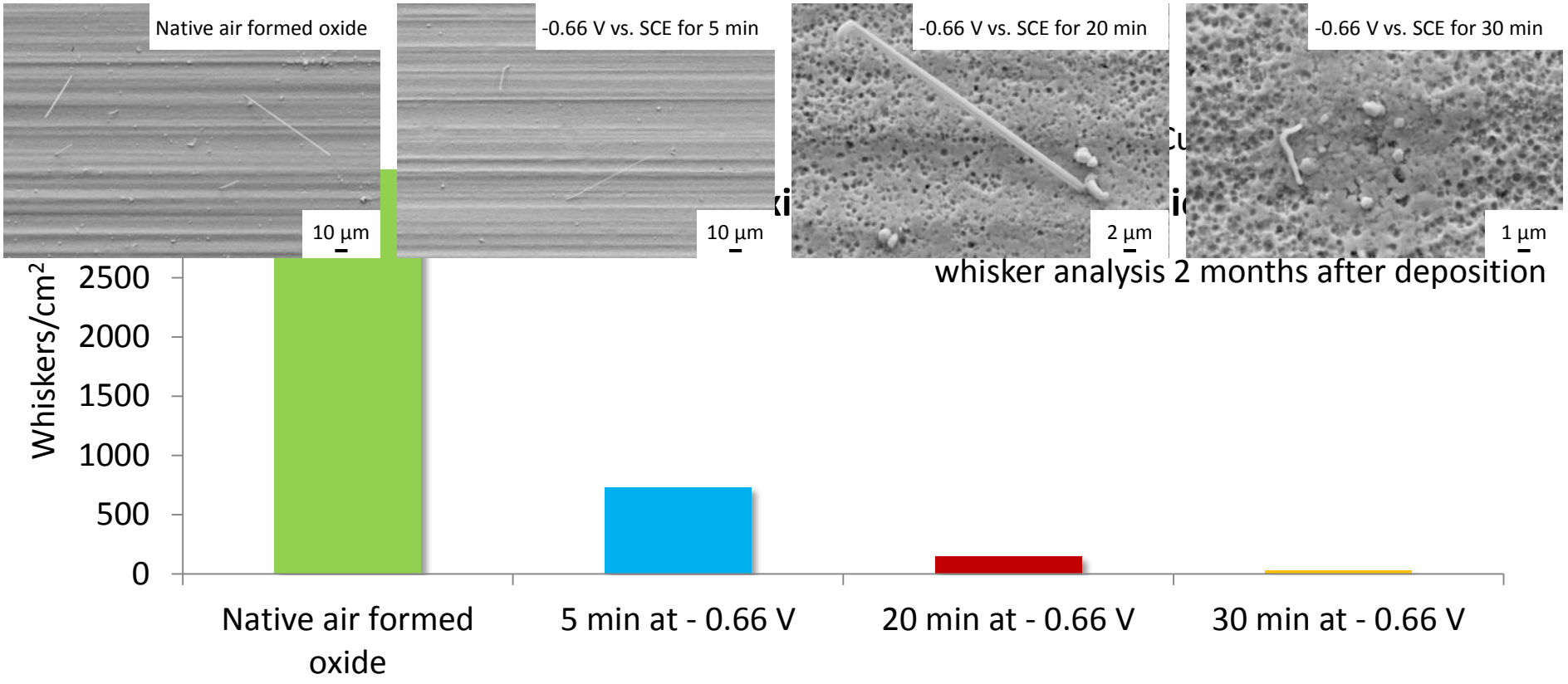
Loughborough University

Whisker density after ~ 2 months storage



Loughborough University

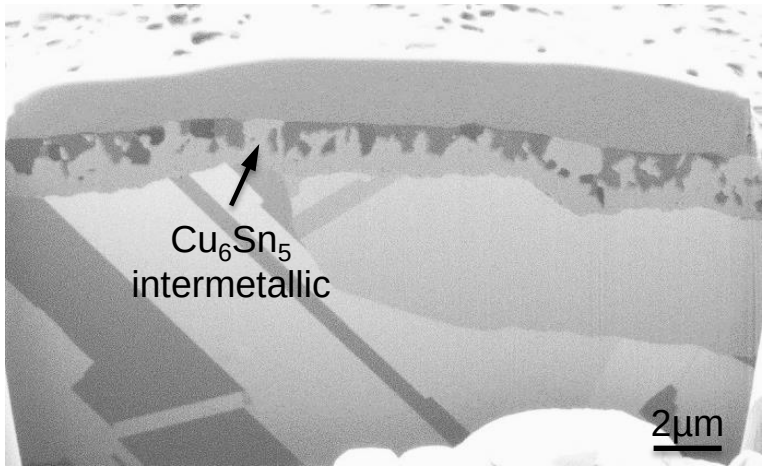
Effect of oxidation time: whisker growth



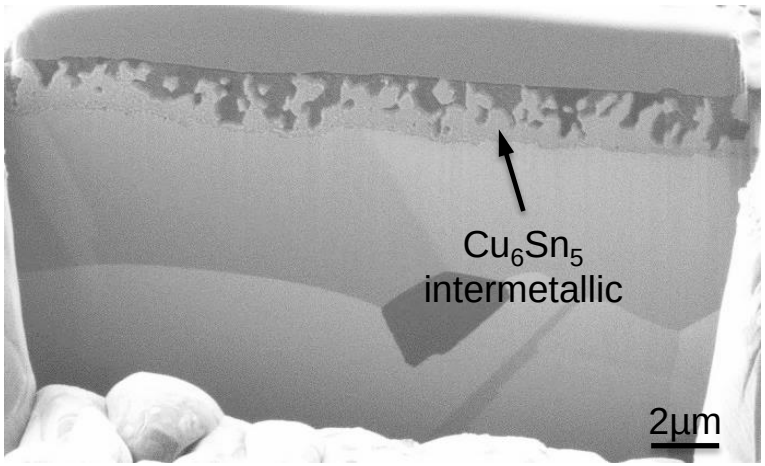
Loughborough University

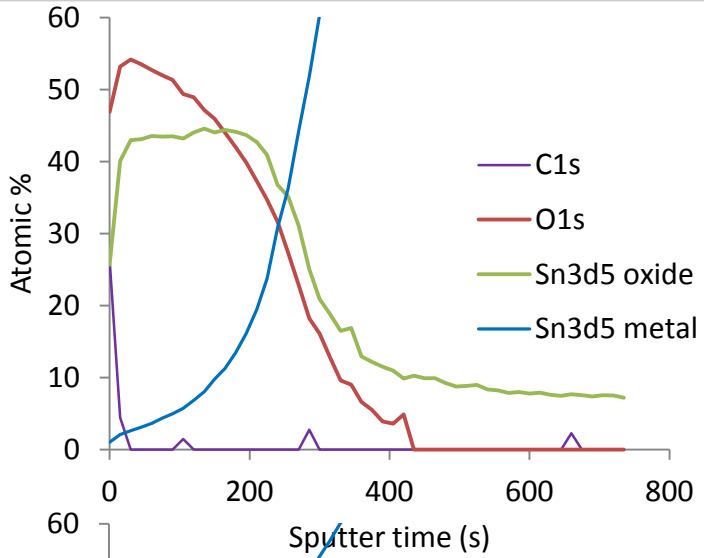
FIB/XPS analysis of SnCu deposits on Cu: ~2 years storage

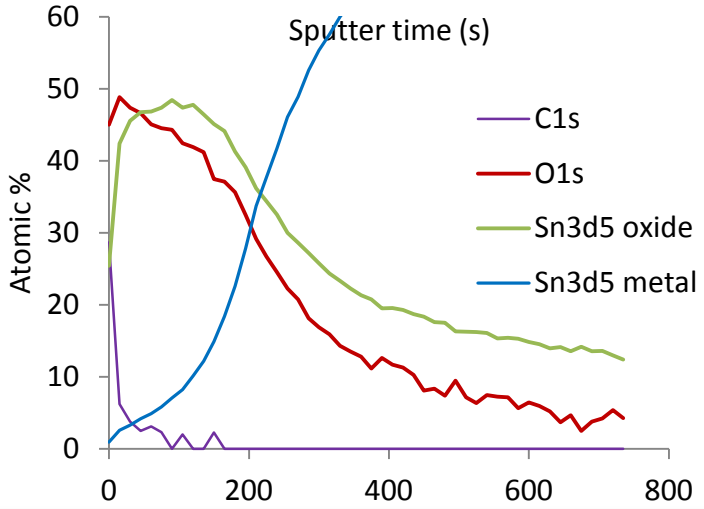
SnCu on Cu
Electrochemical oxidation
at 1.2V
borate buffer



SnCu on Cu
Native air formed oxide

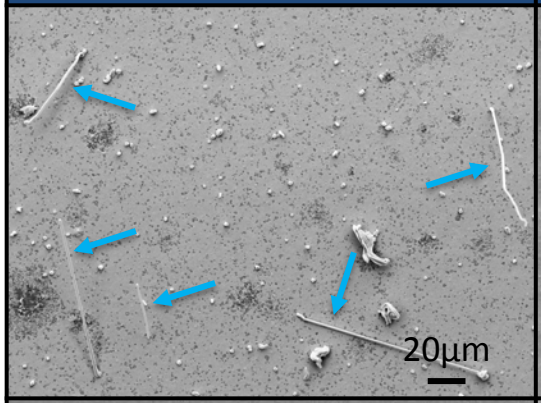
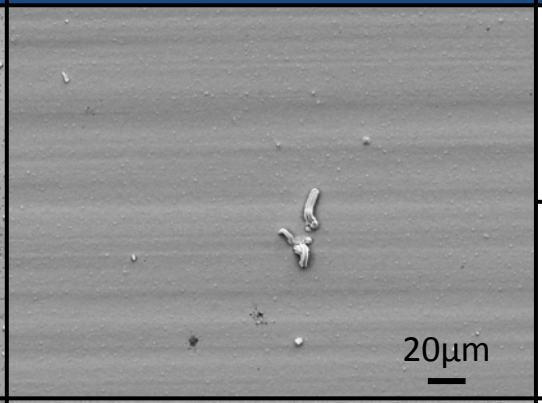
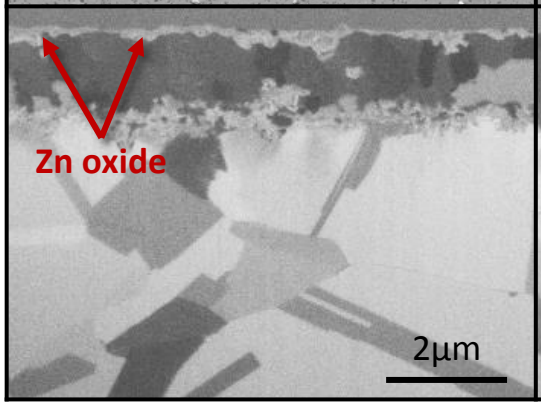
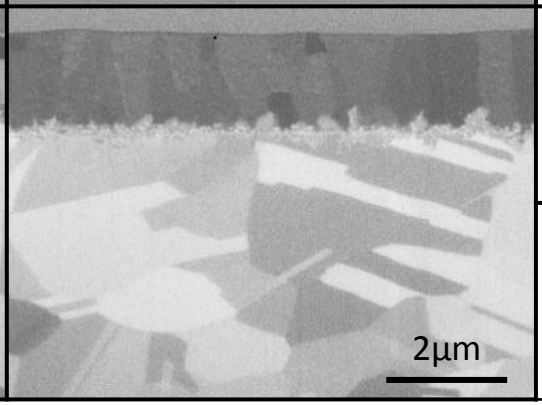






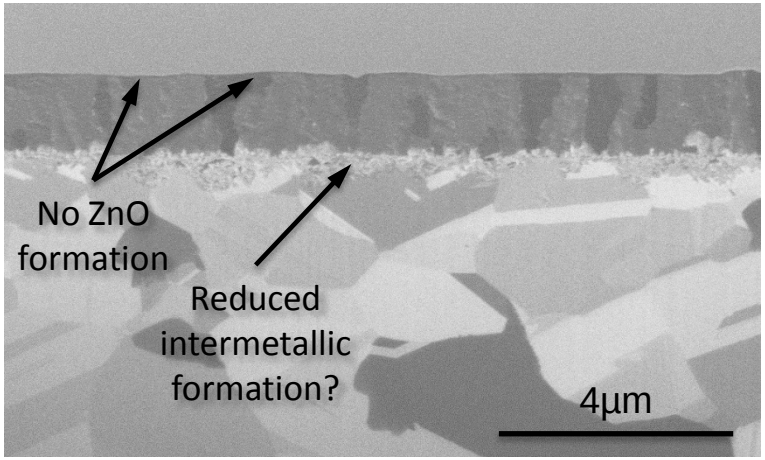
Loughborough University

Sn deposits on brass: whisker growth

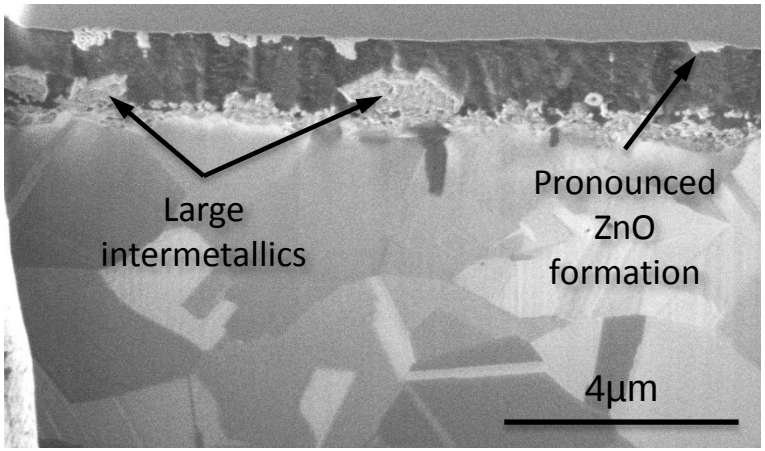
SEM/FIB analysis of 2 µm Sn deposits on brass		Number of whiskers on electrochemically oxidised deposits after 2 years storage (Sample area = 4cm^2)	
Native air formed oxide	Oxidised at 1.2 V vs. SCE	Oxidation potential (V vs SCE)	Average number of whiskers per sample
		1.2 V	6 ± 2
		1.6 V	2.5 ± 2
		2.0 V	3 ± 2

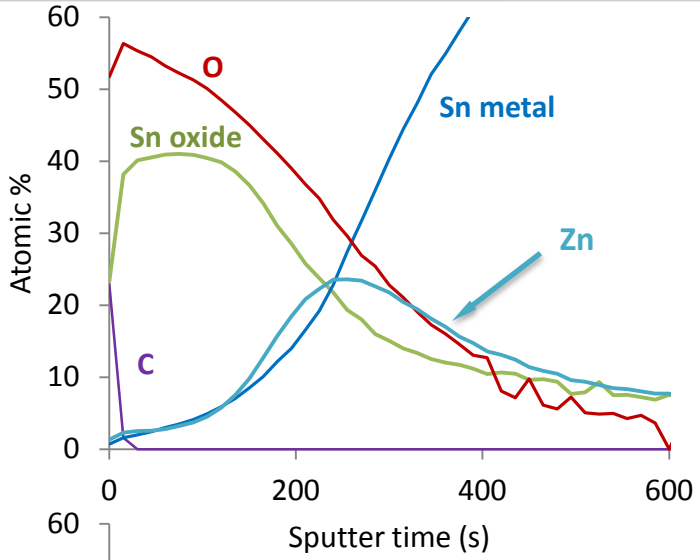
FIB/XPS analysis of Sn deposits on brass: ~30 months storage

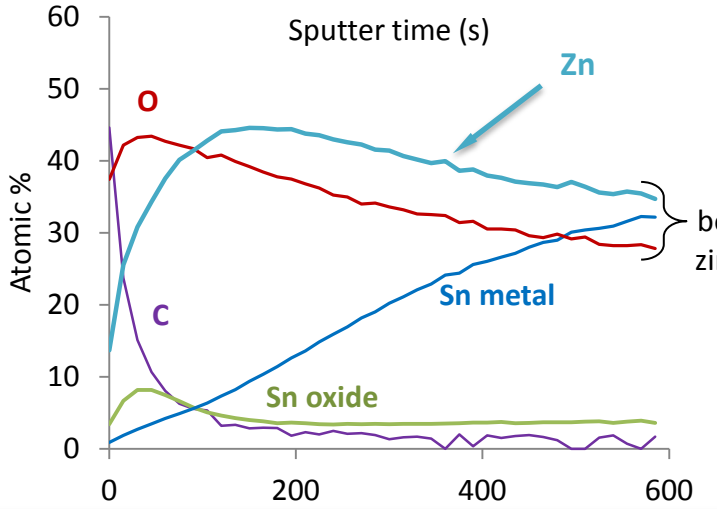
Sn on brass:
Electrochemical oxidation
1.2V
borate buffer



Sn on brass:
Native air formed oxide







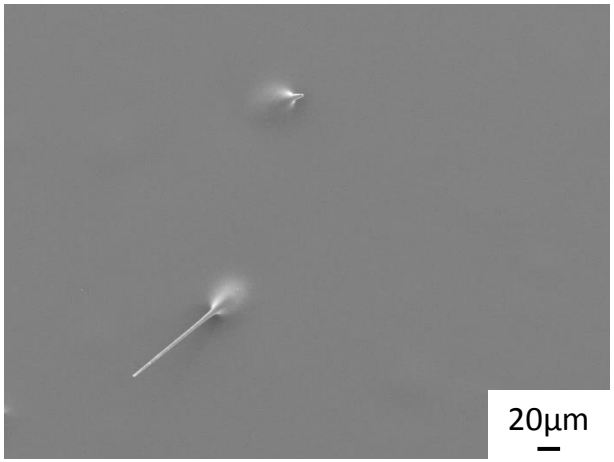
Loughborough University

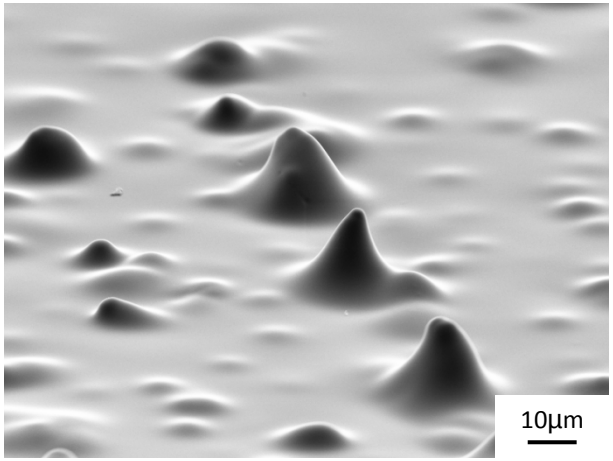
Whisker mitigation mechanism(s)

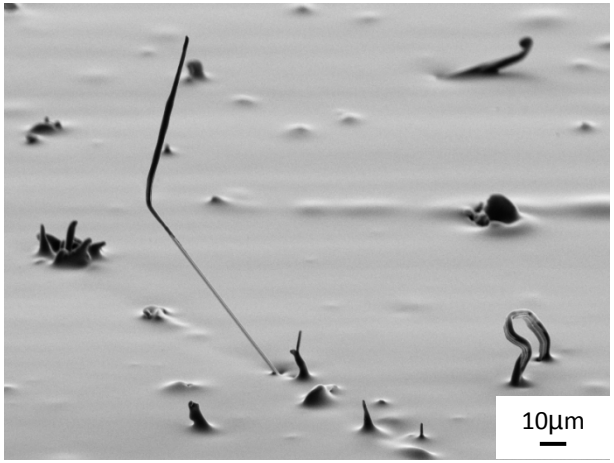
- **For Sn(Cu) deposits on Cu**, IMC formation appears unaffected by electrochemical oxidation and therefore whisker mitigation must simply derived from the increased thickness of the oxide layer
- Although whisker density is greatly reduced long filament whiskers are still produced from electrochemically oxidised SnCu deposits
- Electrochemical oxidation does not reduce the driving force for tin whisker growth (*intermetallic formation*)
- **For Sn deposits on brass**, electrochemical oxidation reduces whisker growth by preventing the formation of Zn oxide at the deposit surface
- Reduced IMC formation in electrochemically oxidised samples may also be an influence

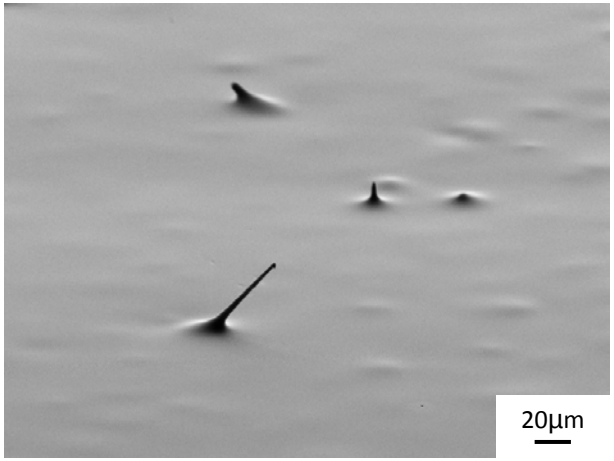
WHISKERMIT: Conformal coating trials

- Evaluation of commercial urethane, acrylic, silicone and UV cure coatings
- Samples cured both at room temperature and in the oven
- Model coating materials (UV cure) prepared with tailored properties (flexible to rigid)
- Evaluated using tin deposits on brass substrates





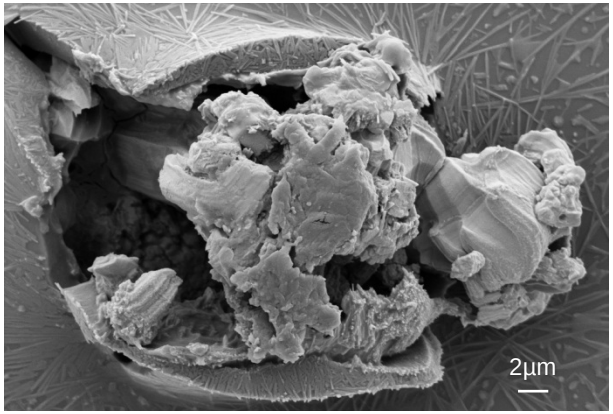




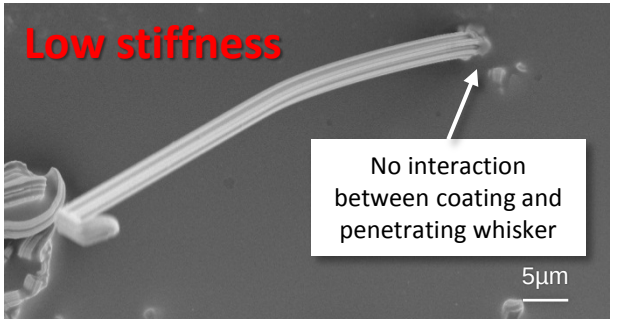
Loughborough University

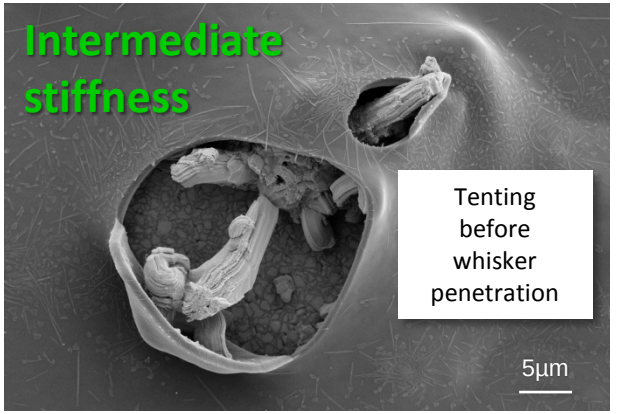
Effect of physical properties on whisker growth

- Original **WHISKERMIT** project demonstrated correlation between coating modulus and whisker growth/penetration
- Develop conformal coatings that are specifically designed to prevent whisker growth



Penetrating whisker 'flattened' by interaction with stiff coating





The next step…..

WHISKERMIT 2

Improving the whisker mitigation properties of polymeric conformal coatings

Summary

- Whiskers do not always do what you expect!
- Whisker morphology and density may be modified by control of deposition parameters
- Greatly increased whisker growth for tin deposits on brass
- Silver may not be an ideal barrier layer material
- Electrochemical oxidation has the potential to mitigate whisker growth
- Conformal coatings optimised to mitigate whisker growth are required

Any questions?