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Electrical characteristics of Sn-whiskers

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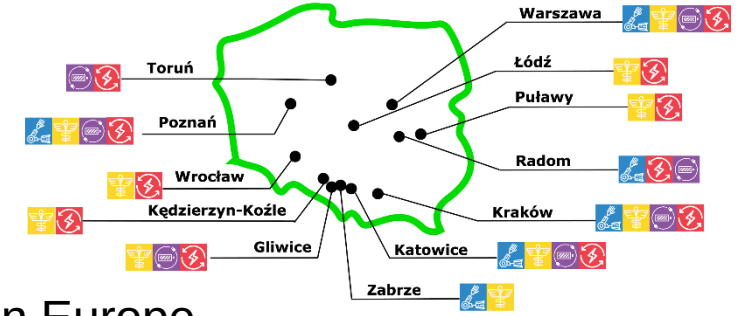
Outline/Agenda

1. Introduction and goal of the work
2. Measurements in the air
3. Measurements in the vacuum
4. Breakdown voltage, current capacity
5. SONNET simulations
6. Summary

Łukasiewicz Network



- The third-largest research network in Europe
- Located in Central and Eastern Europe

- Over 4200 engineers and scientists that run 440 laboratories in the country

- A first-class research infrastructure
- 22 Institutes in 12 cities

Łukasiewicz – Institute of Microelectronics and Photonics

- Mission: We develop technologies of the future in response to the challenges of the modern world.

- Vission: We want to be a leading partner in implementing valuable technologies and products in **microelectronics and photonics.**

- Key features:

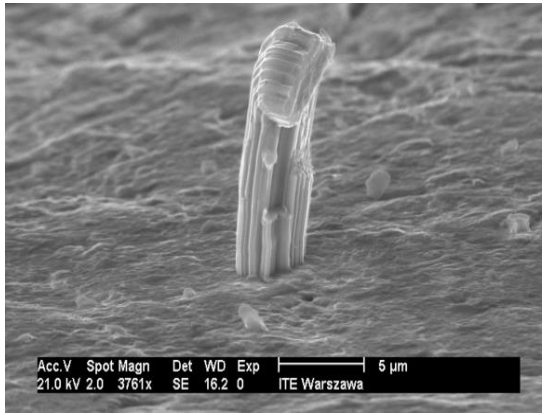
✓The research is organized around technology lines for: optoelectronics subassemblies, silicon subassemblies, wide band gap semiconductor subassemblies (GaN, SiC), **electronic materials – fabrication and testing**, sensors

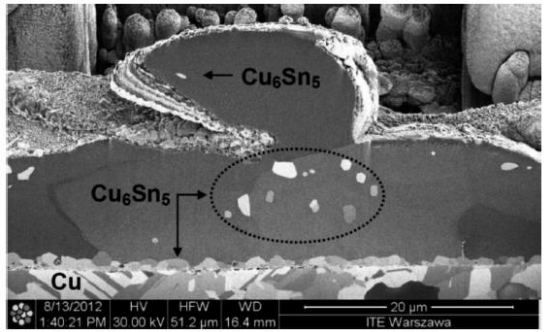
✓14 R&D expert groups

✓400 highly qualified employees

Sn whiskers

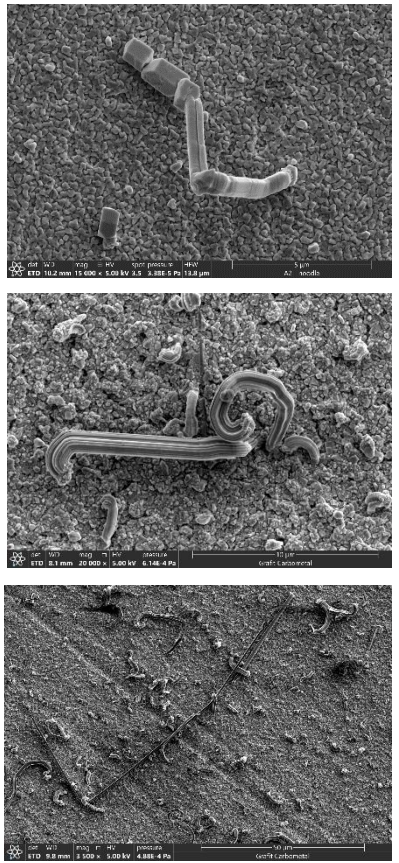
- Crystals growing from Sn surface as the result of compressive stress relaxation.
- Serious threat to the circuit's reliability.
- The growth depends on the compressive stress generated in the Sn layer, including mechanical and thermal effects…..
- There is the influence of diffusion, CTE mismatch, Sn grain size, oxidation, and many others……
- Galaxy 7 (2000) and Galaxy 3R (2006) were lost because of the Sn whisker shortcut.





Whiskers – electrical conductivity

- ✓ Hundreds of the works were carried out on Sn whisker growth
- ✓ „A few” works concerning the electrical characterization of tin whiskers in the literature
- ✓ The bridging risk can be categorized into two types: fixed (attached) whiskers and free (unattached) whiskers.



Whiskers – electrical conductivity

The failure modes include:

- ✓ permanent short circuits in low-current applications
- ✓ transient short circuits in applications where the current is high enough to cause the whisker to fuse open
- ✓ metal vapor arcing in a vacuum
- ✓ debris/contamination resulting from vibration, which frees loose whiskers that can interfere with optical surfaces or bridge exposed electrical conductors

Goal and hypotheses of the work

The goal of this work was to measure the electrical conductivity of Sn whiskers grown under atmospheric and vacuum conditions.

Questions:

Atmospheric-grown whiskers in the air will be oxidized. Sn oxides are dielectrics/insulators. The breakdown voltage will be observed.

Vacuum-grown whiskers will not be oxidized, or will oxidize less. No breakdown voltage will be observed (?).

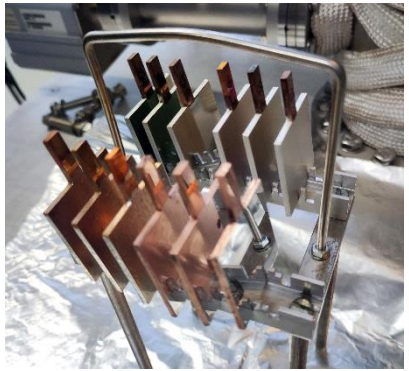
Atmospheric and vacuum-grown whiskers will differ in morphology. Different values of the current can be measured (?).

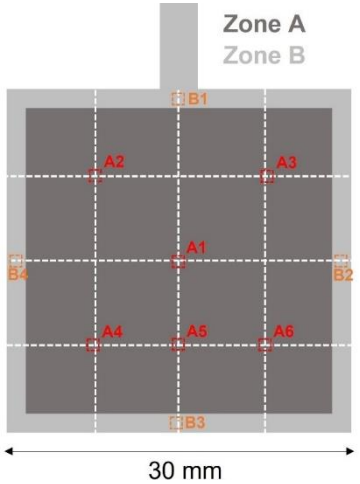
Whiskers can induce the current in neighboring conductive paths (?).

Experimental

Aging:

- ✓ V1: constant 50ºC in vacuum for 1000h
- ✓ V2: 25-125˚ C cycling in vacuum, 1000 cycles (1000h), pressure: 8.3x10-6 mbar





Samples:

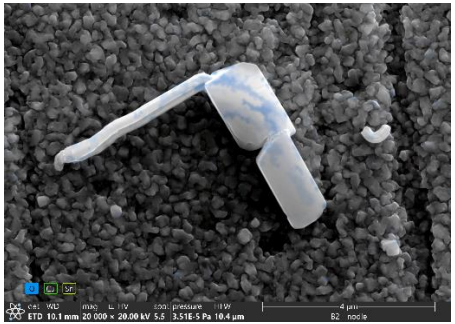
- ✓ PVD Sn
- ✓ Electroplated Sn

Measurements:

- ✓ In the air
- ✓ In the vacuum

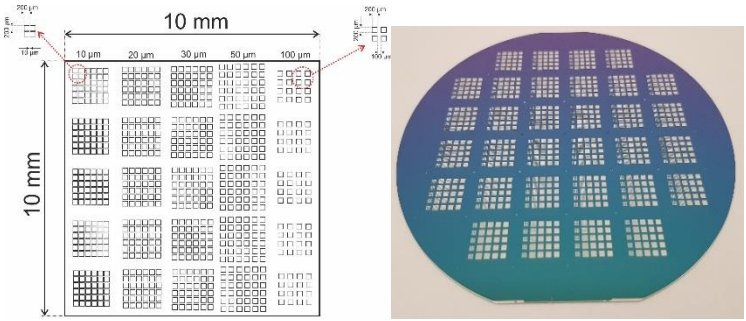
- ✓ Needle

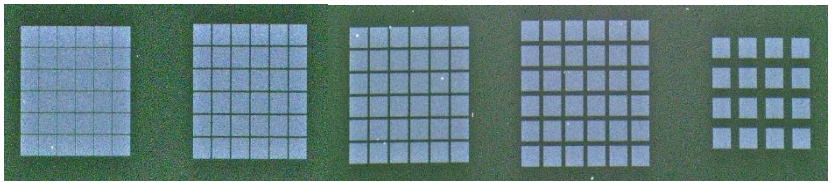
- ✓ Nodule



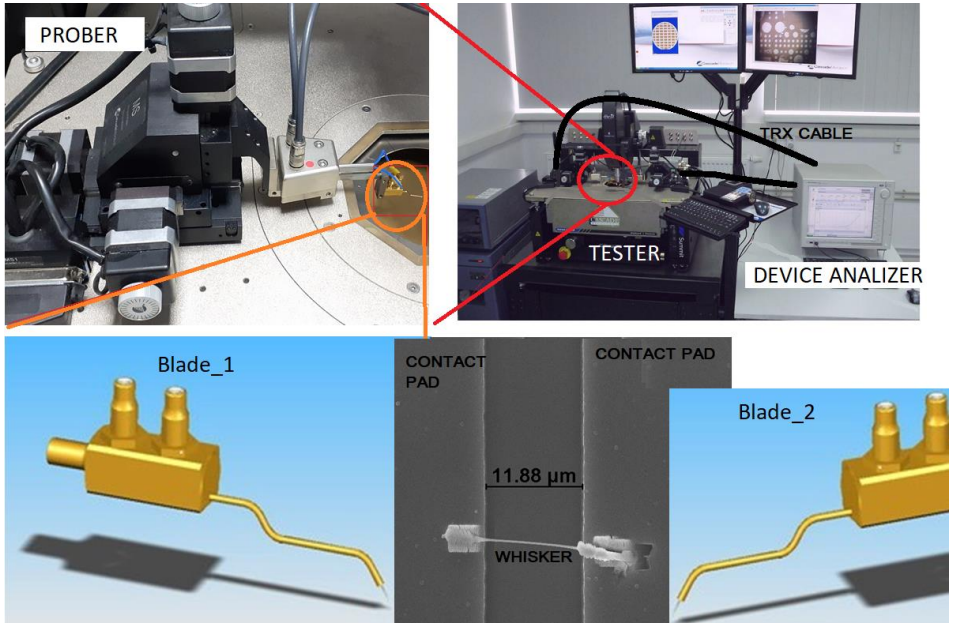
- ✓ Segment („minecraft”)

Method 1 - Measurment in the air



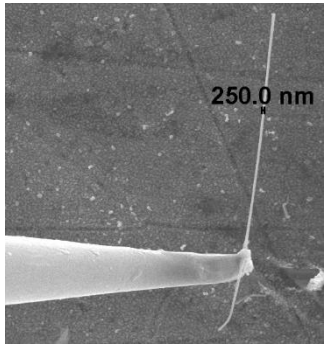


4 inch Si/SiO2 wafer with groups of contact pads

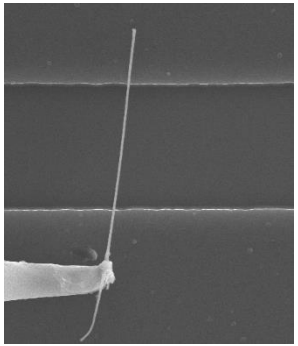


Electrical pads prepared by photolithography

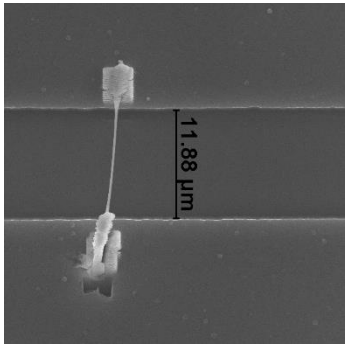
Measurement in the air



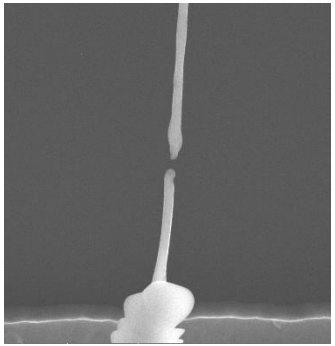
Tungsten needle welding



Transfer to contact pads



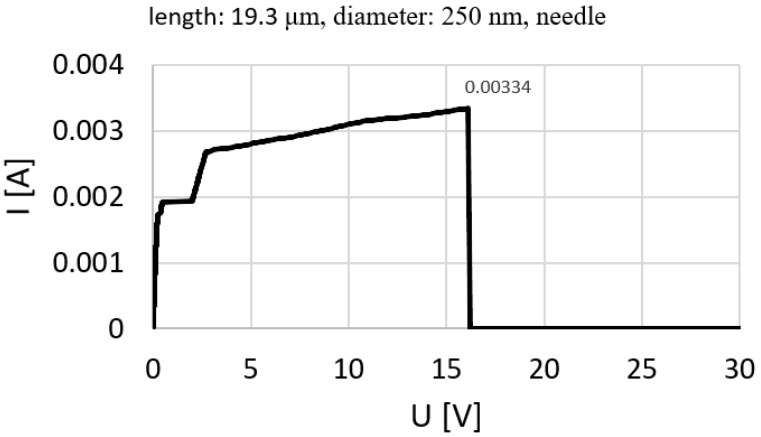
Welding to contact pads

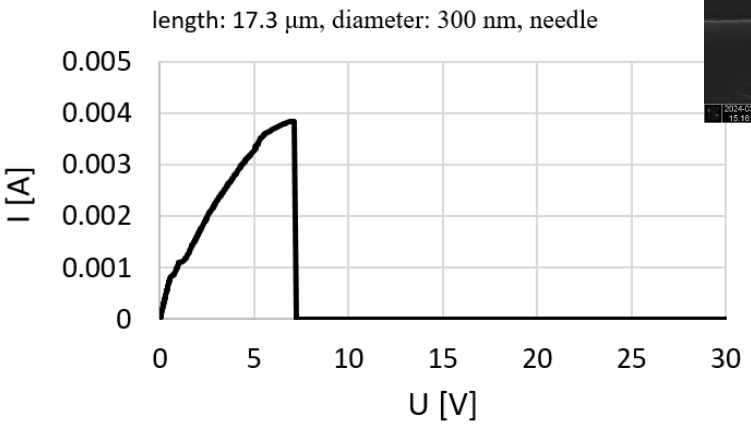


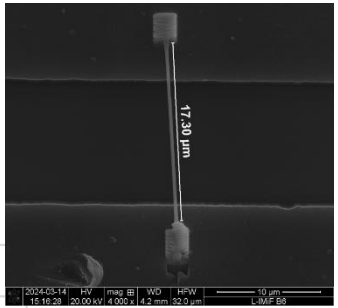
Whisker fuse

- The FIB manipulator needle is attached to the whisker using deposition techniques in focused ion beam (FIB) technology.
- The whisker is then picked up from the substrate and transported between the electrical pads.
- The ends of the whisker are welded to the contact pads, after which the manipulator needle is cut off from the whisker.
- Electrical measurements are conducted outside the FIB vacuum chamber.

Measurement in the air







PVD samples aged 50°C, 1000 hours, vaccum 8.3x10E-6 Pa

- The current shows a linear increase, indicating an ohmic contact.
- Whisker "a": (1) there is a linear I-V curve with a resistance of 100 ohms. At around 16.1 V, the current drops.
- Whisker "b": (1) there is a linear I-V curve with a resistance of 0.6 kOhms. At approximately 7.1 V, the current drops.

Method 2 - Measurement in the vacuum

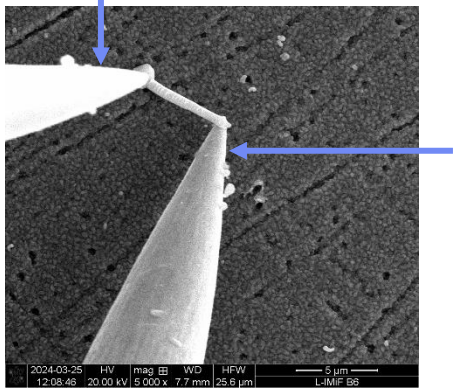
SEM/FIB system - Helios NanoLab 600 DualBeam

Micromanipulators Kleindiek

KEYSIGHT Semiconductor Device Analyzer

Measurement in the vacuum

Blade_1

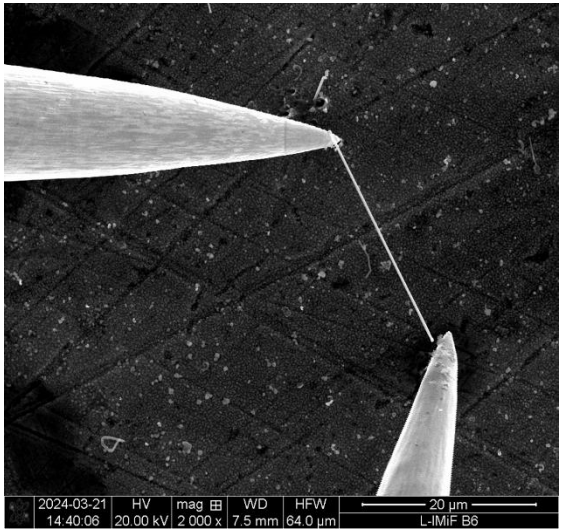


Blade_2 (under **lifted** end)

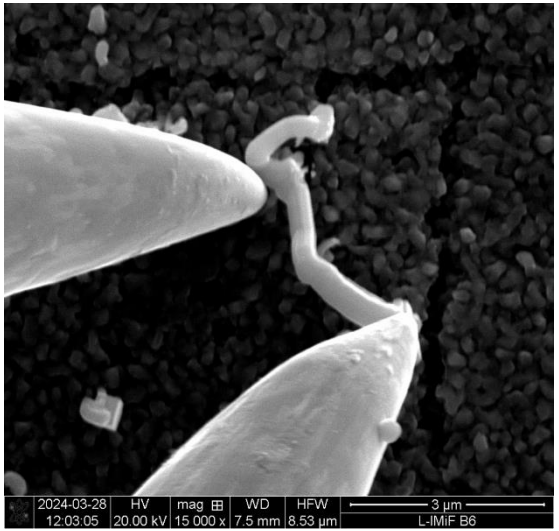
- Measurements were conducted using Kleindiek micromanipulators.
- A sample was placed inside the vacuum chamber of the SEM/FIB system.
- Two tungsten blades were used to establish an electrical connection.
- The presence of oxide on the surface of the whisker caused the capacitor to break down when subjected to a sufficiently high voltage, allowing current to flow.
- No oxide was present between blade 1 and the tin, as the surface had been scratched with the tip.

Measurement in the vacuum

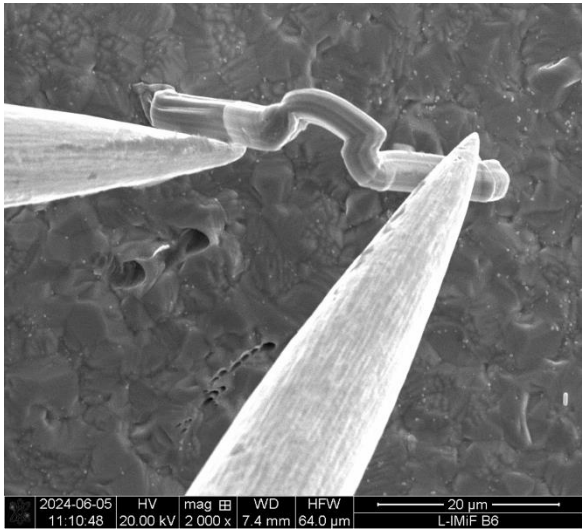
Needle



Nodule



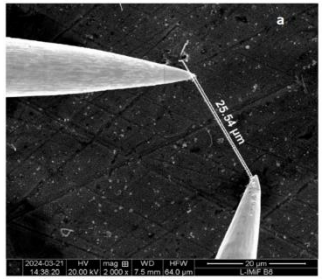
Segment („minecraft”)

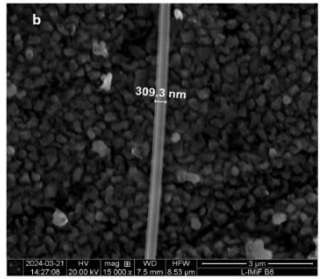


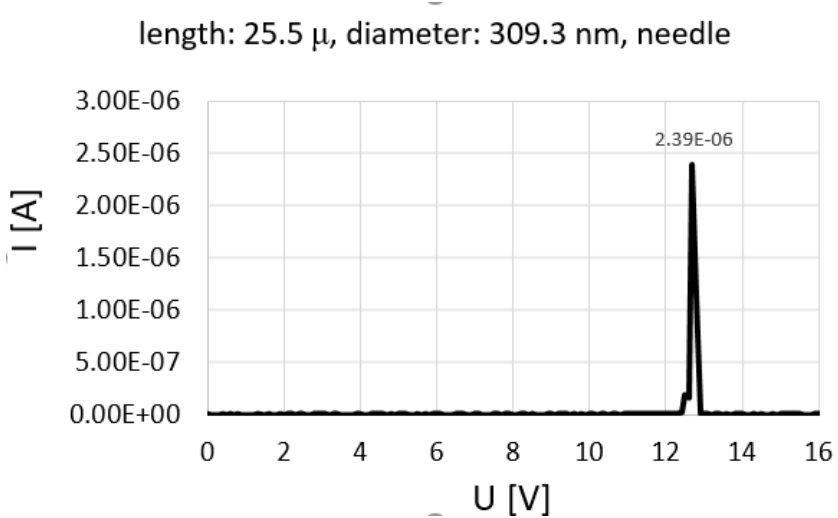
I-V characteristics - PVD samples

- ✓ The current flow started at 12.5V, → and an oxide at the whisker's surface started to leak.
- ✓ At 12.7 V (corresponding to a current of 2.4 μA), the current drops since the whisker was fused.
- ✓ The current density J_{br} is 10^3 times lower than measured in air (in a vacuum, heat can be radiated only by electromagnetic emission or transferred into the substrate at one end of the whisker).

PVD samples aged 50℃, 1000 hours, vaccum 8.3x10E-6 Pa





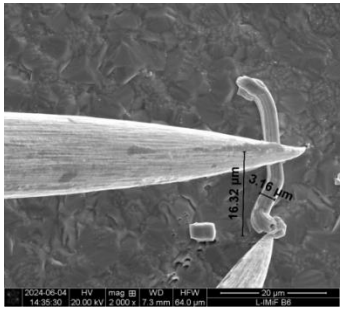


I-V characteristics – electrodeposition samples

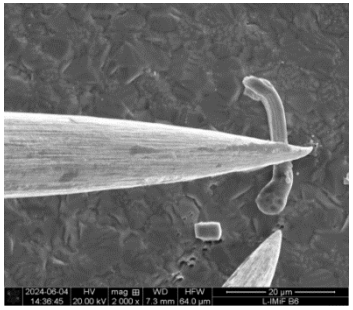
- ✓ The current flow appears at about 1V and increases to 1.4 mA.
- ✓ The whisker has not fused.
- ✓ The melting of Sn causes the electrical break.
- ✓ Afterward, a solidification (recrystallization) occurs.
- ✓ The current density J_{br} is 10 times higher than in needle whisker.

U_{br} = 17.0 V
I_{br} = 1.4 mA
J_{br} = 1.79×10^8 A/m^2

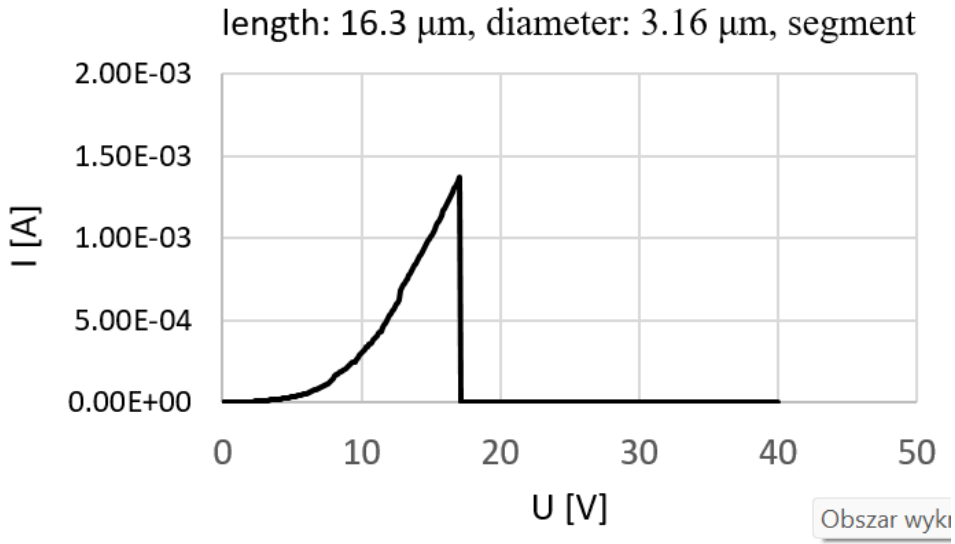
aged 50℃, 500h, vaccum 8.3x10E-6 Pa



before bias



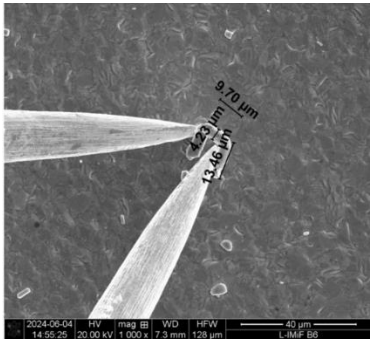
after bias

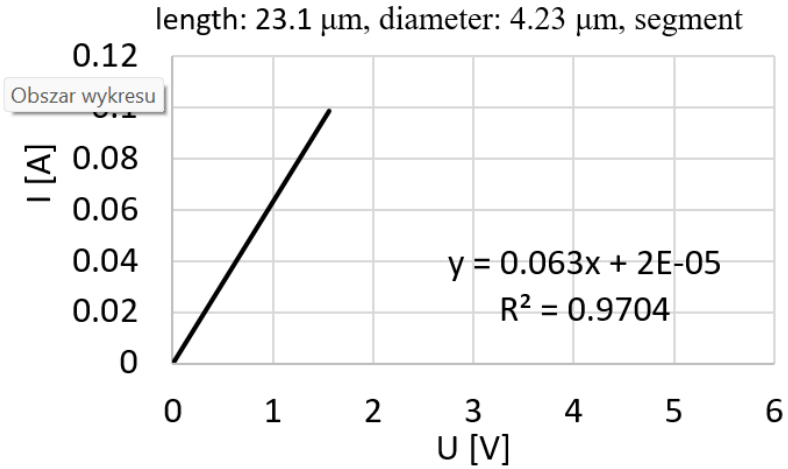


I-V characteristics – electrodeposition samples

- ✓ The initial flow starts at zero voltage, indicating an absence of surface oxide.
- ✓ The I-V characteristic is linear, and the whisker has not fused.
- ✓ Its current capacity exceeds the maximum current of the device analyzer, which is 100 mA.

aged 90℃,1400h ambient

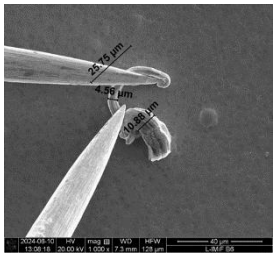




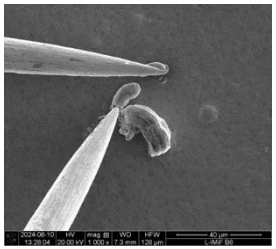
I-V characteristics – electrodeposition samples

- ✓ The whiskers were not fused during the measurement.
- ✓ They can withstand a current flow of 100 mA.
- ✓ It melted and recrystallized.
- ✓ The irregular I-V characteristics is attributed to the softening of tin as the temperature increases, which causes the contact to become unstable and leads to random fluctuations in resistance.

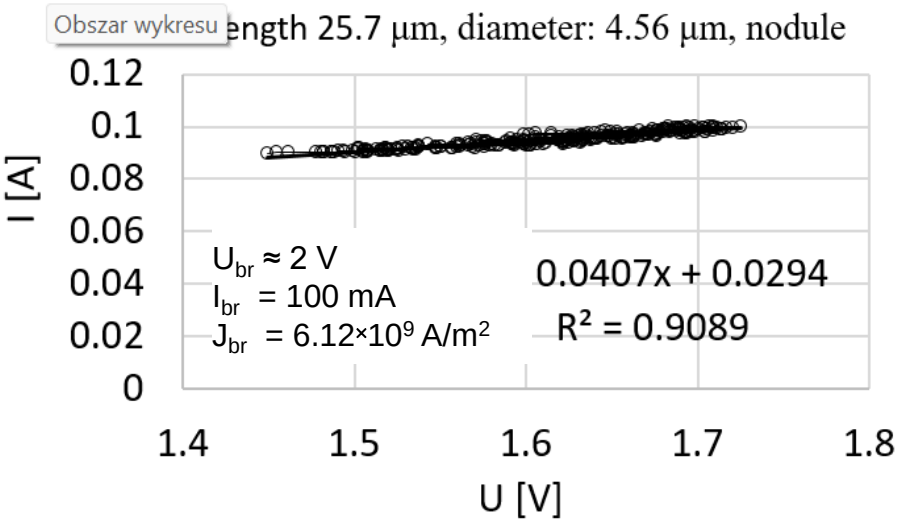
aged 90°C,1400h ambient



before bias

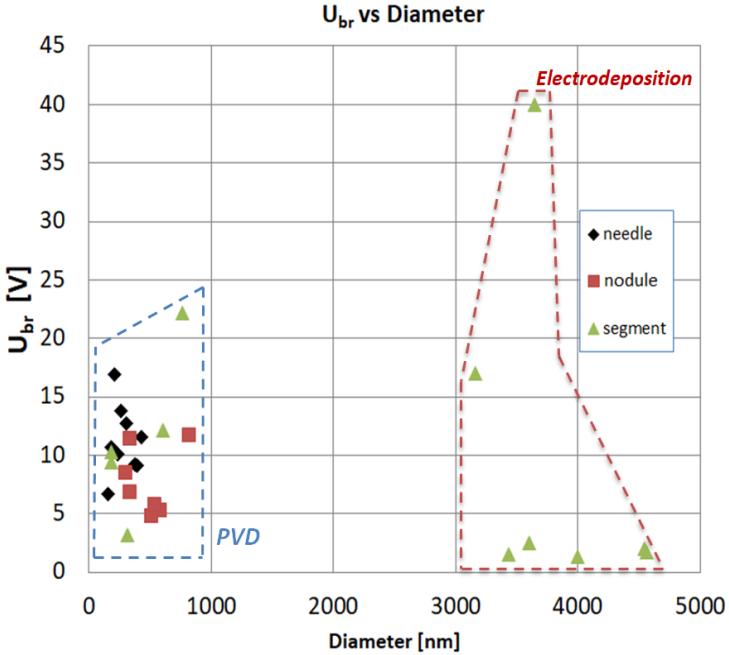


after bias



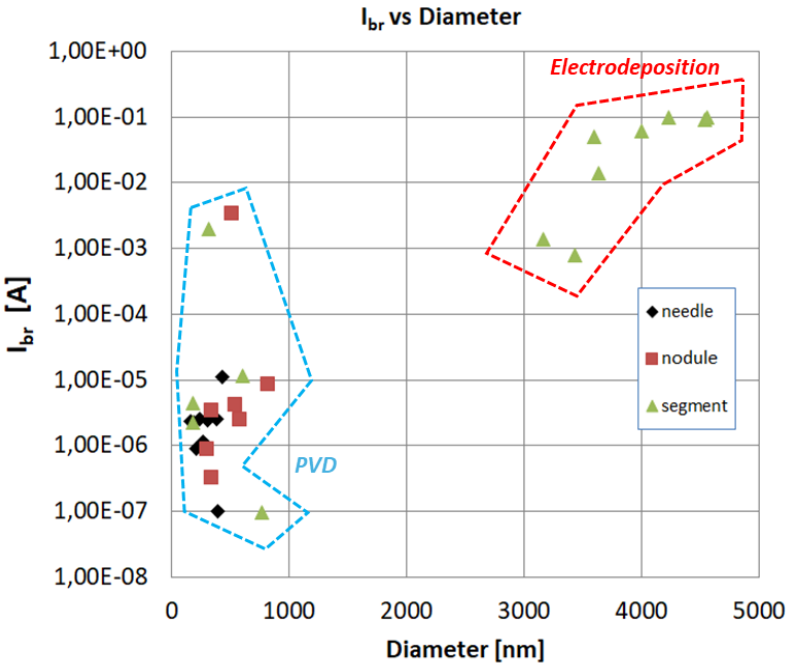
Breakdown voltage

- ✓ Certain segment whiskers exhibit a significantly lower breakdown voltage.
- ✓ The variations in breakdown voltage are caused by the presence or absence of oxide on the surface of the whiskers.
- ✓ When aged in a vacuum, the samples undergo oxidation until they are measured.
- ✓ Segment whiskers from electrodeposited samples have a larger diameter (indicated by the red), but their breakdown voltage is not significantly higher.

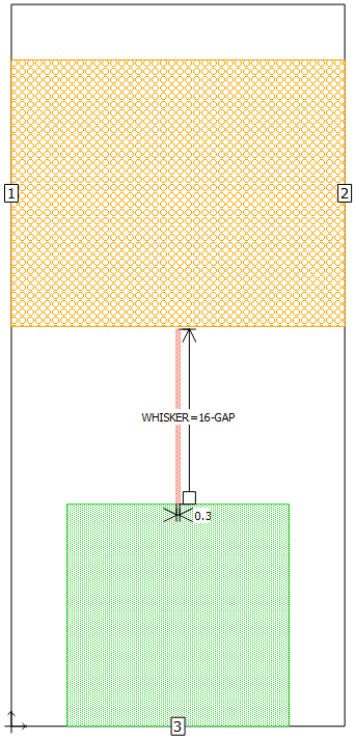


Current capacity

- ✓ Segment whiskers exhibit a significantly higher current capacity.
- ✓ The diameter of the whisker influences the difference in current capacity.
- ✓ The current capacity of segment-type tin (Sn) whiskers can exceed 100 mA.
- ✓ Typically, segment whiskers do not fuse; instead, their electrical connection can be interrupted due to shape changes that occur from thermal deformation, melting, and solidification.
- ✓ The whiskers grown on electrodeposited samples are primarily of the thick segment type.



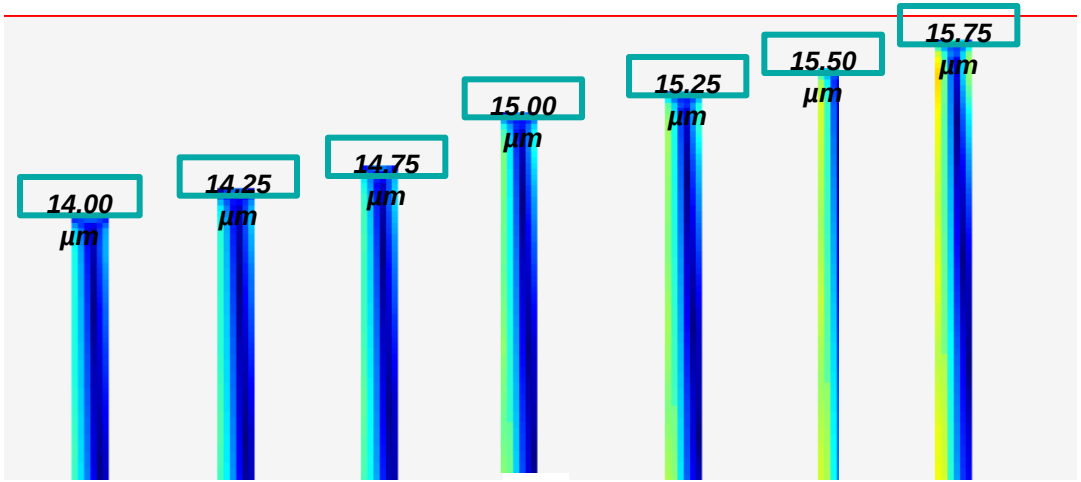
SONNET simulation of whisker growth in 16µm gap

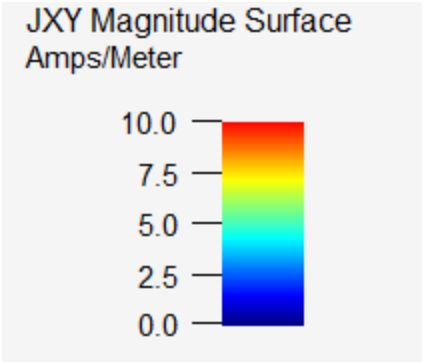


Model assumptions

- ✓ Frequency: 10GHz, Voltage: 1V
- ✓ Port 1 - 50Ω source, port 2, 3 - 50Ω sink
- ✓ Substrate: 200µm FR4
- ✓ Green pad (Sn): thickness 0.25µm Sn, 25µm x 25µm
- ✓ Orange pad (Cu): thickness 0.25µm Cu, 25µm x 35µm
- ✓ Whisker: rectangular cross section 0.3x0.3µm Sn
- ✓ Whisker length: changing from 16-14 µm
- ✓ Mesh grid: X: 0.01µm, Y:0.05µm

SONNET simulation of whisker growth in 16µm gap





✓ At 14 µm of whisker length, induction of the electric field is visible.

Simulation authors: Krzysztof Zaraska & Monika Machnik, Łukasiewicz-IMiF

Summary

✓A total of forty-one I-V characteristics were measured for whiskers grown on different tin substrates.

✓The current capacity of these whiskers varies depending on the measurement method used.

- Whiskers measured in air exhibit only minor variations in current capacity.
- In contrast, whiskers measured in a vacuum display variations on the order of five magnitudes.

✓When measured in a vacuum chamber, a **capacitor** is formed between the whisker and the tungsten blade. This "temporary" capacitor is charged by the current until the insulator breaks down.

Summary

- ✓ The electrical conductivity of the whiskers measured in a vacuum differs from that measured in air **by three orders of magnitude**. This difference can be attributed to the heat transport to the air and contact pads.
- ✓ Both measurement methods can simulate potential short circuits in real-world scenarios.
  - Without an oxide layer: This simulates whisker growth under vacuum conditions (similar to those in space), which can lead to a direct short circuit in spacecraft.
  - With an oxide layer: This simulates whisker growth in ambient conditions (similar to those on Earth), which may cause a short circuit in spacecraft at a later stage.

Summary

✓The breakdown voltage varies between **2 and 17 volts**, depending on the thickness of the oxide at the surface of the whisker.

✓The current capacity ranges **from microamperes (µA) to over 100 milliamperes (mA).**

✓The current capacity of certain **segment-type whiskers**, commonly referred to as “minecraft” whiskers, can exceed the equipment's **current limit of 100 mA**.

Acknowledgment

„Current Capacity and Effects of Vacuum of Tin Whiskers”
ESA Contract No. 4000140874/23/NL/AS

WHISFUSE

cidetec surface engineering

BME ETT ELEKTRONIKAI TECHNOLÓGIA TANSZÉK

Łukasiewicz Institute of Microelectronics and Photonics