

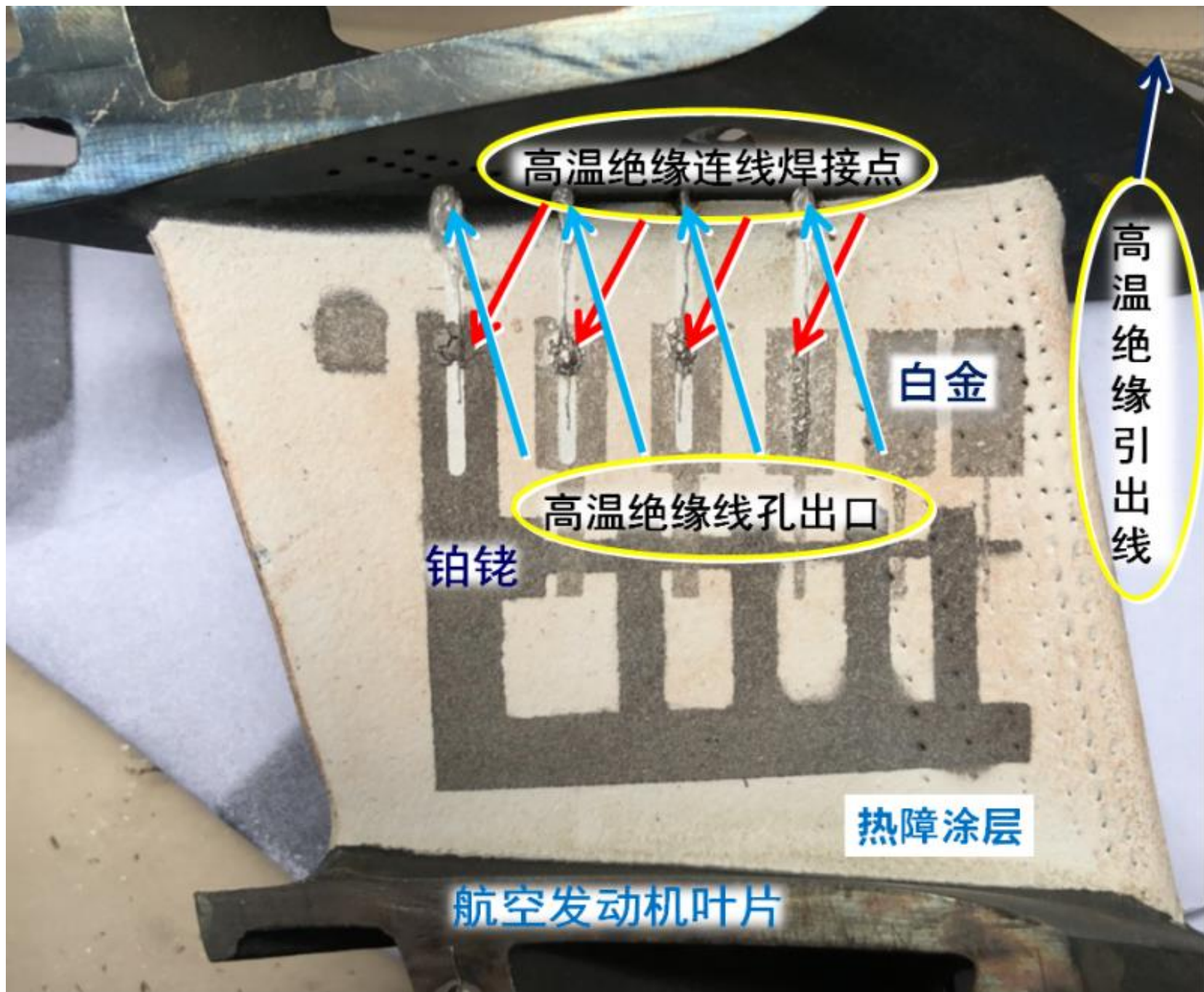




上海交通大学  
20181121  
我办公室的立  
体型书架  
直观省空间

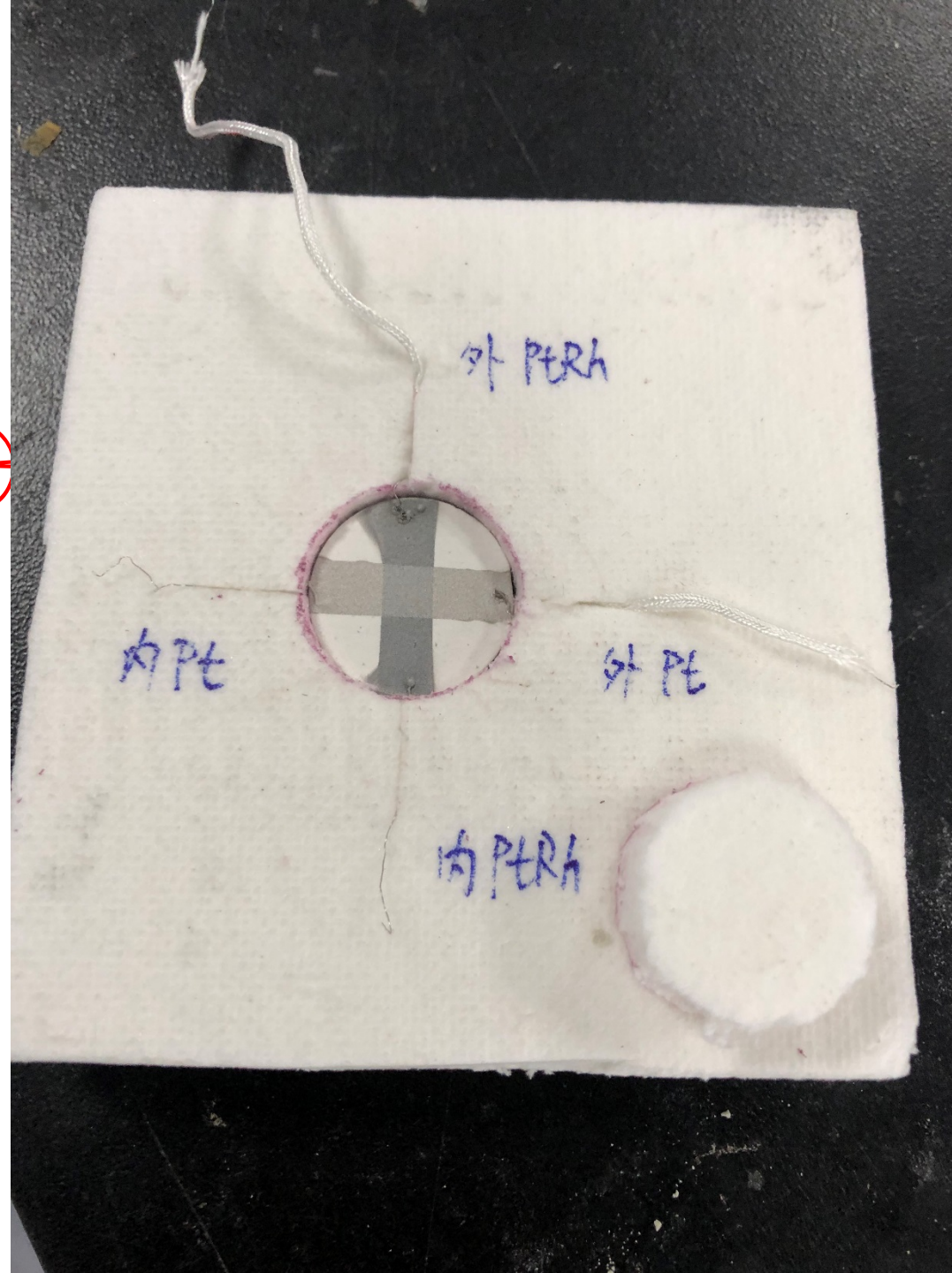


航空发动机涡轮叶片表面集成的高温传感器阵列



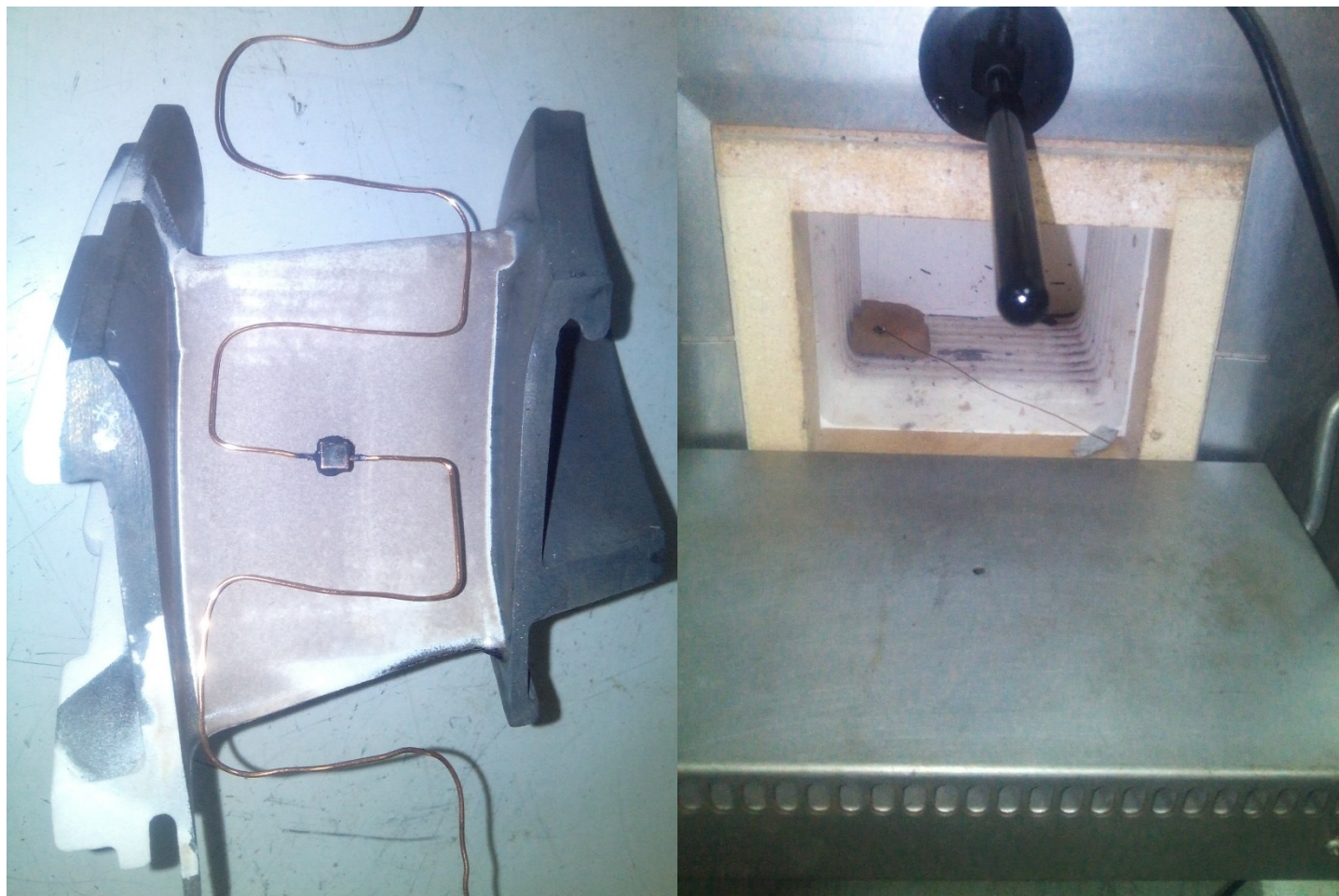


航空发动机TBC  
隔热测量  
双层传感器

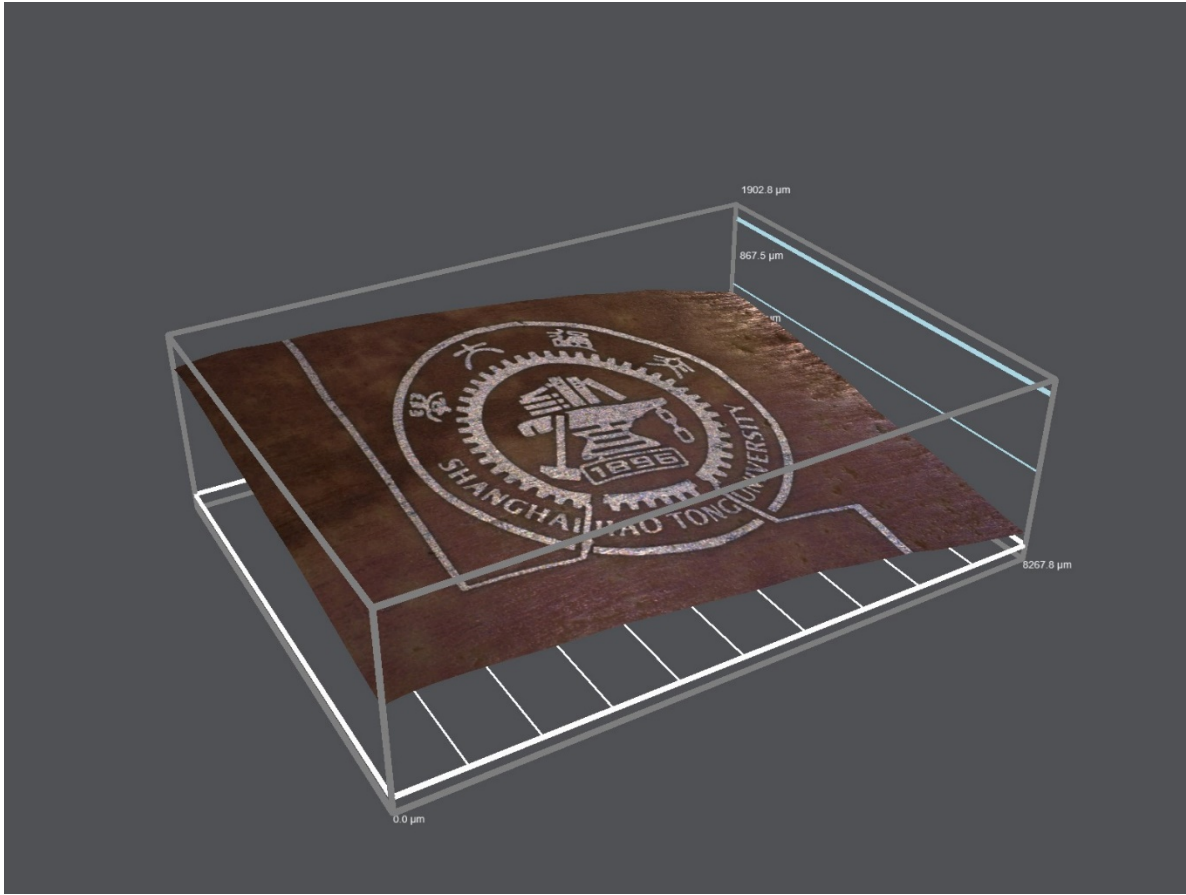




SAW  
高温温度测量  
无线遥感



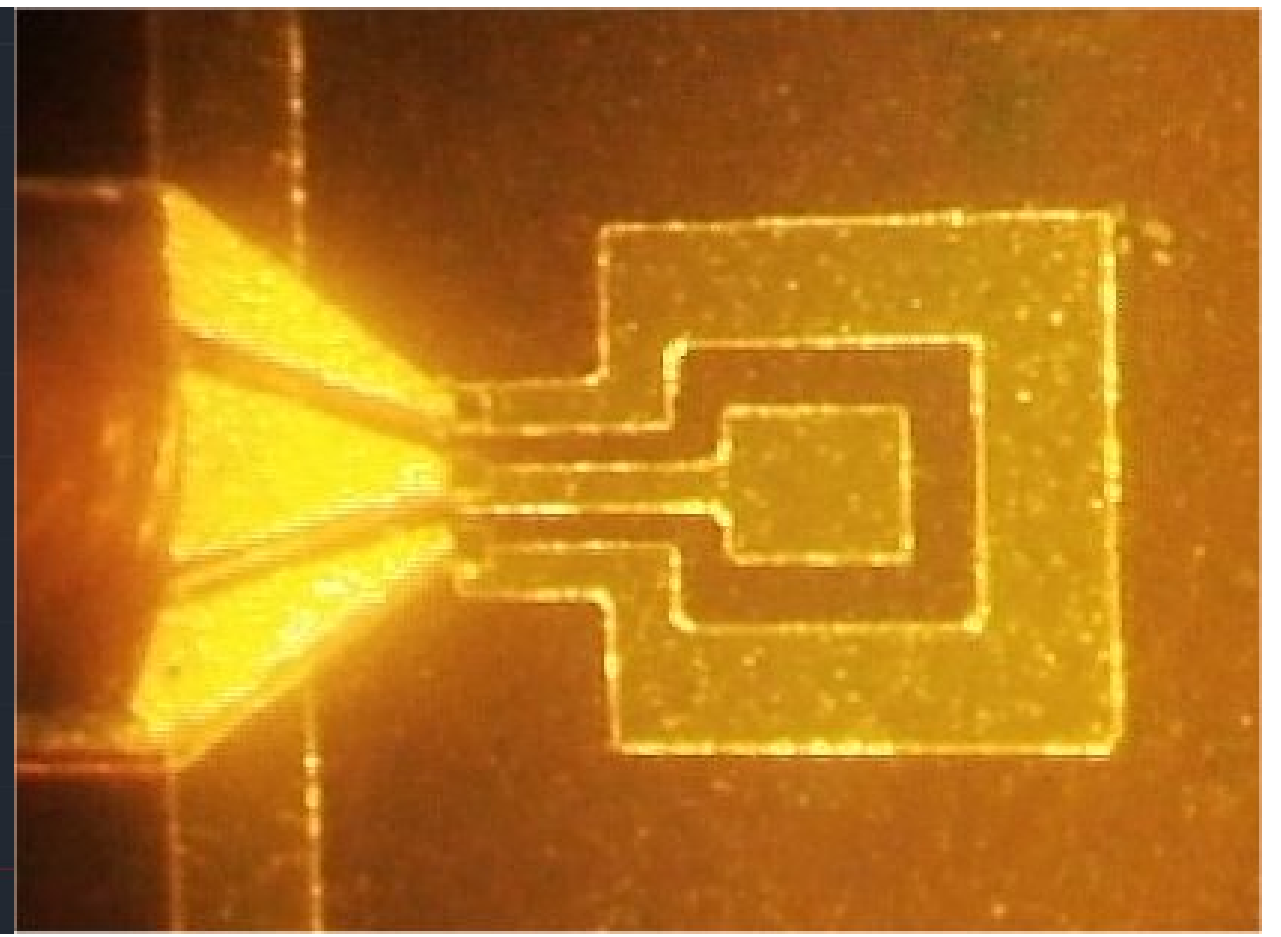
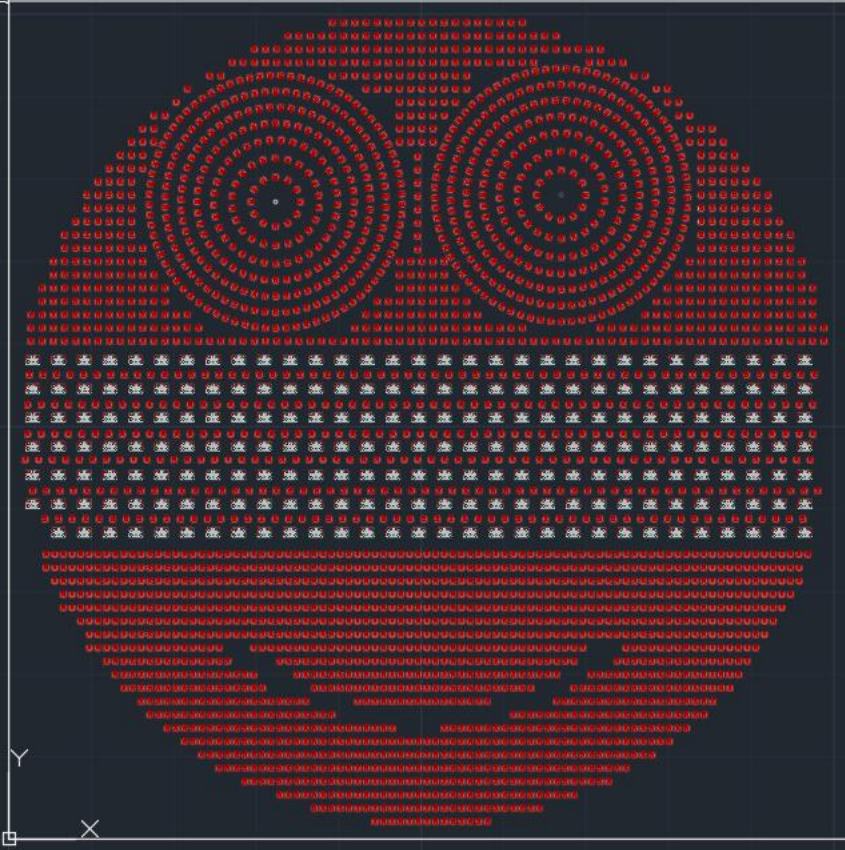




交大在3D叶片上

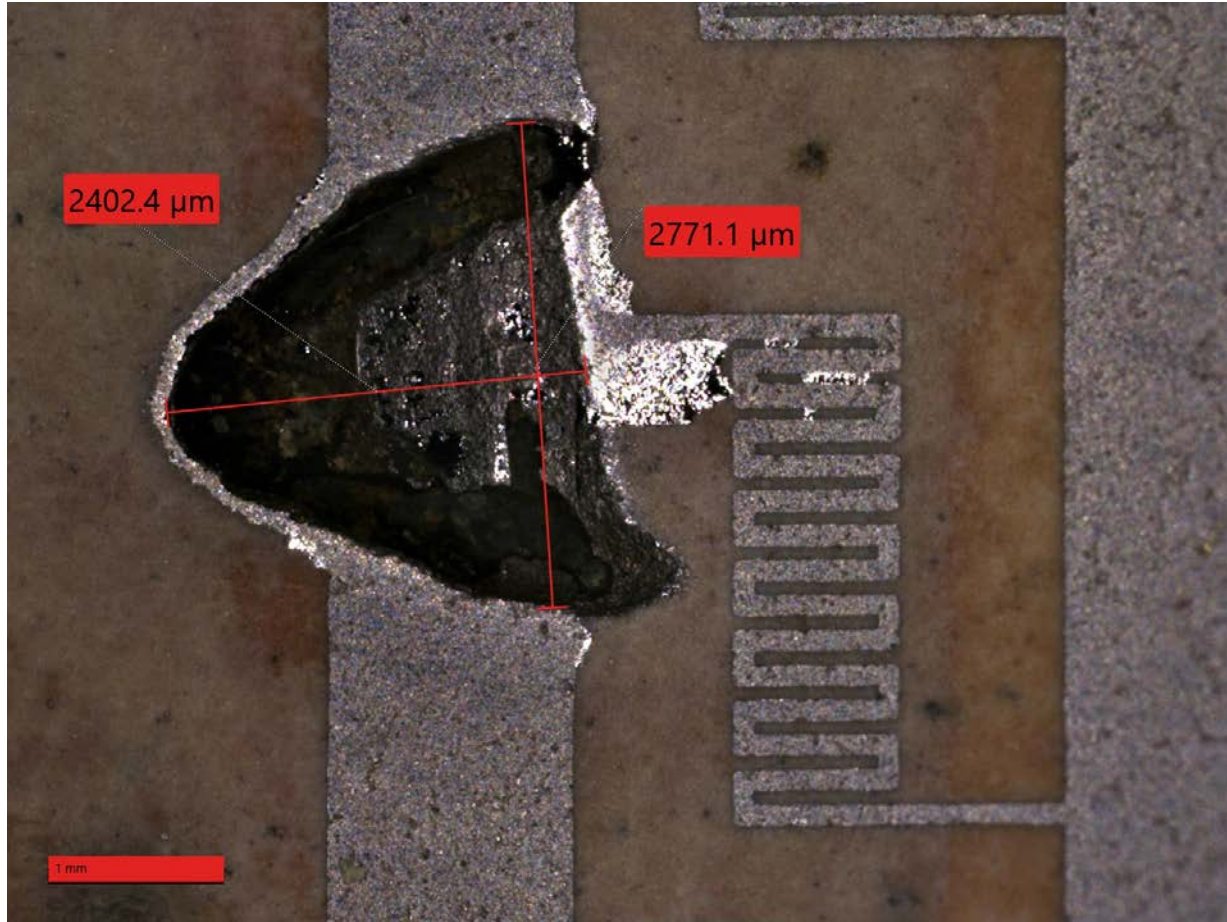


[-](俯视)二维线图



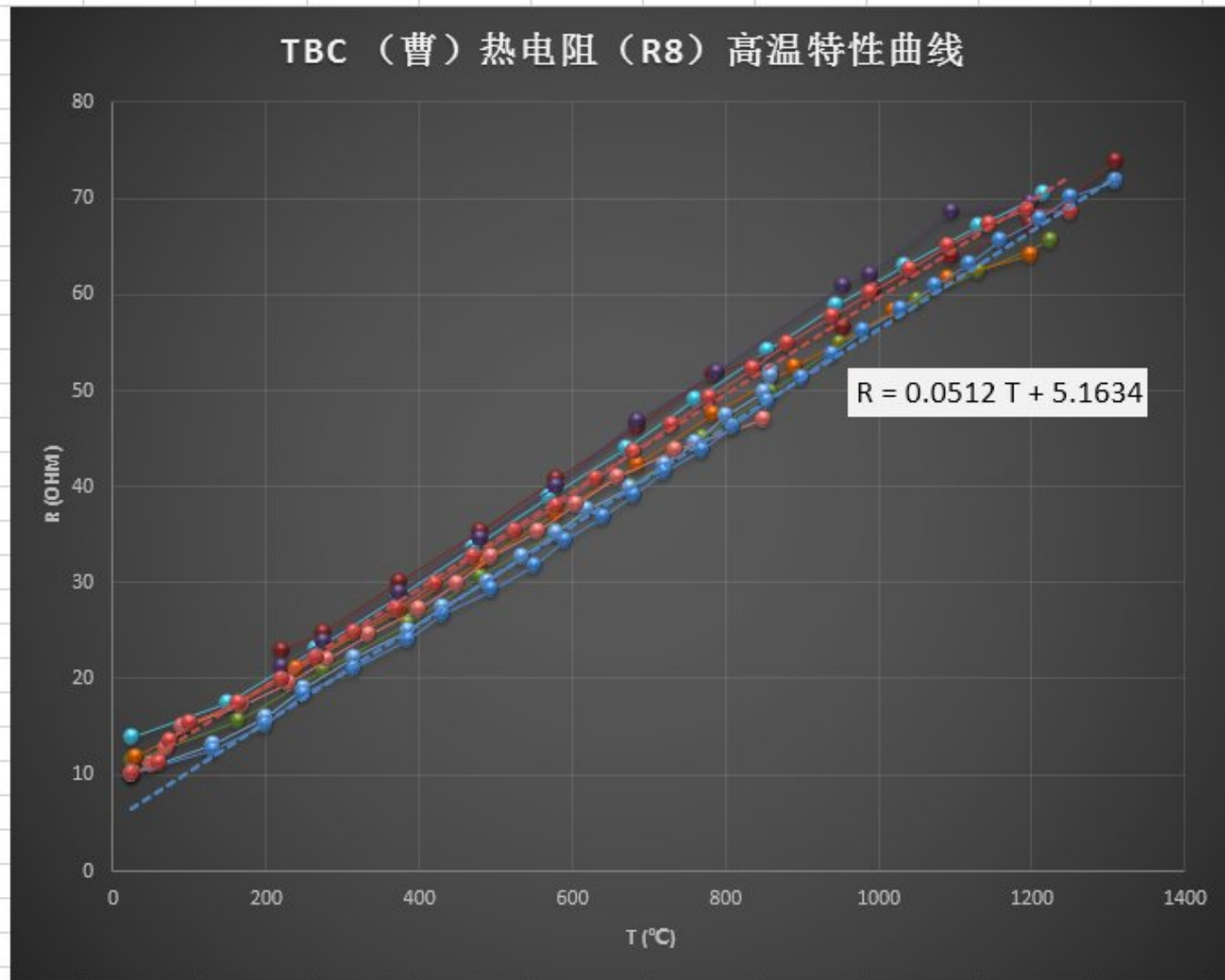
FBAR 在笑





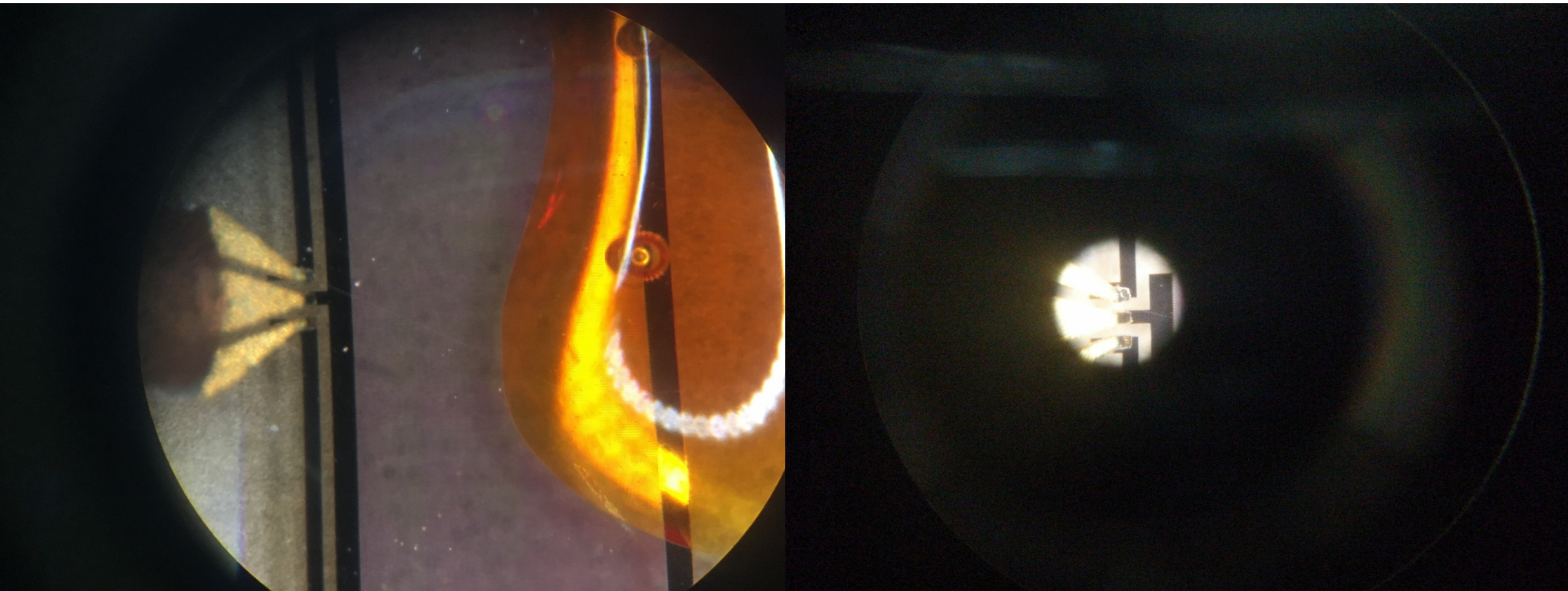
MEMS thin film 集成的细致





高温 · 叶片 · 传感

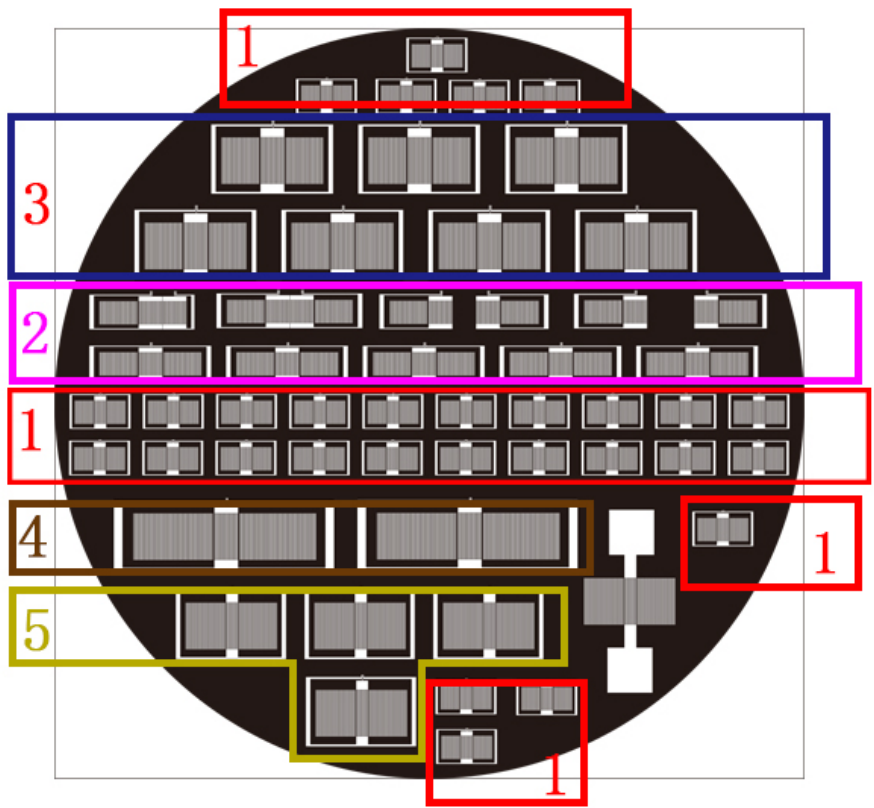
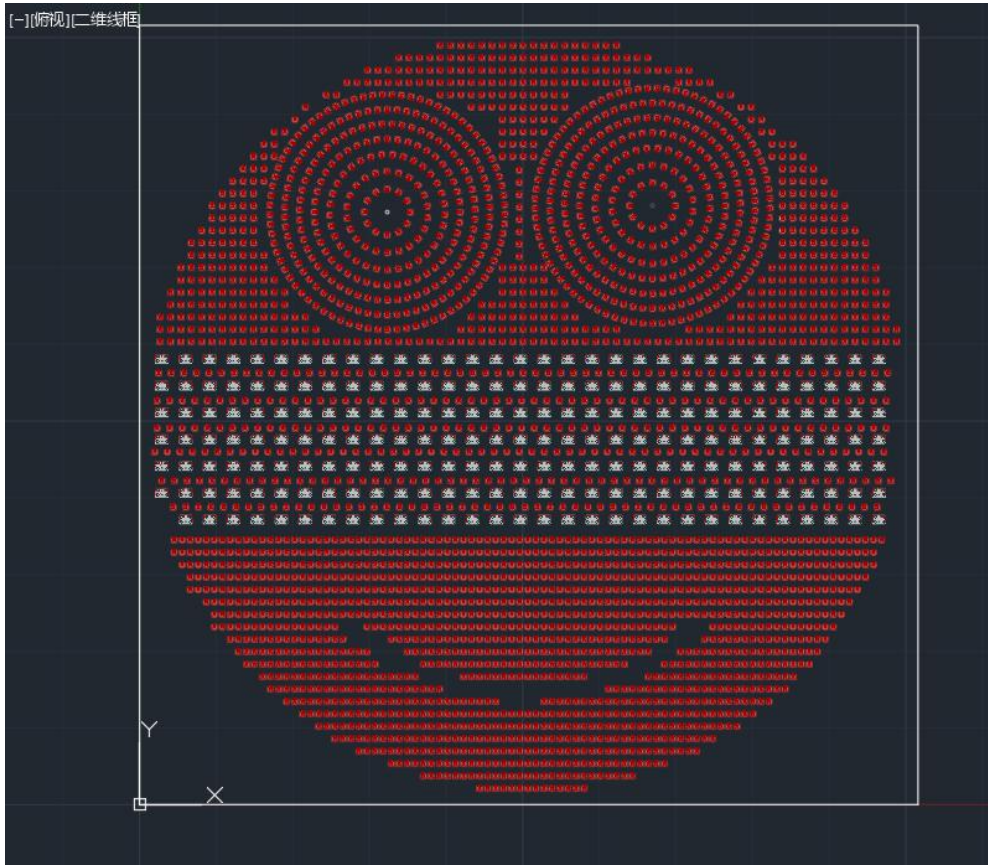




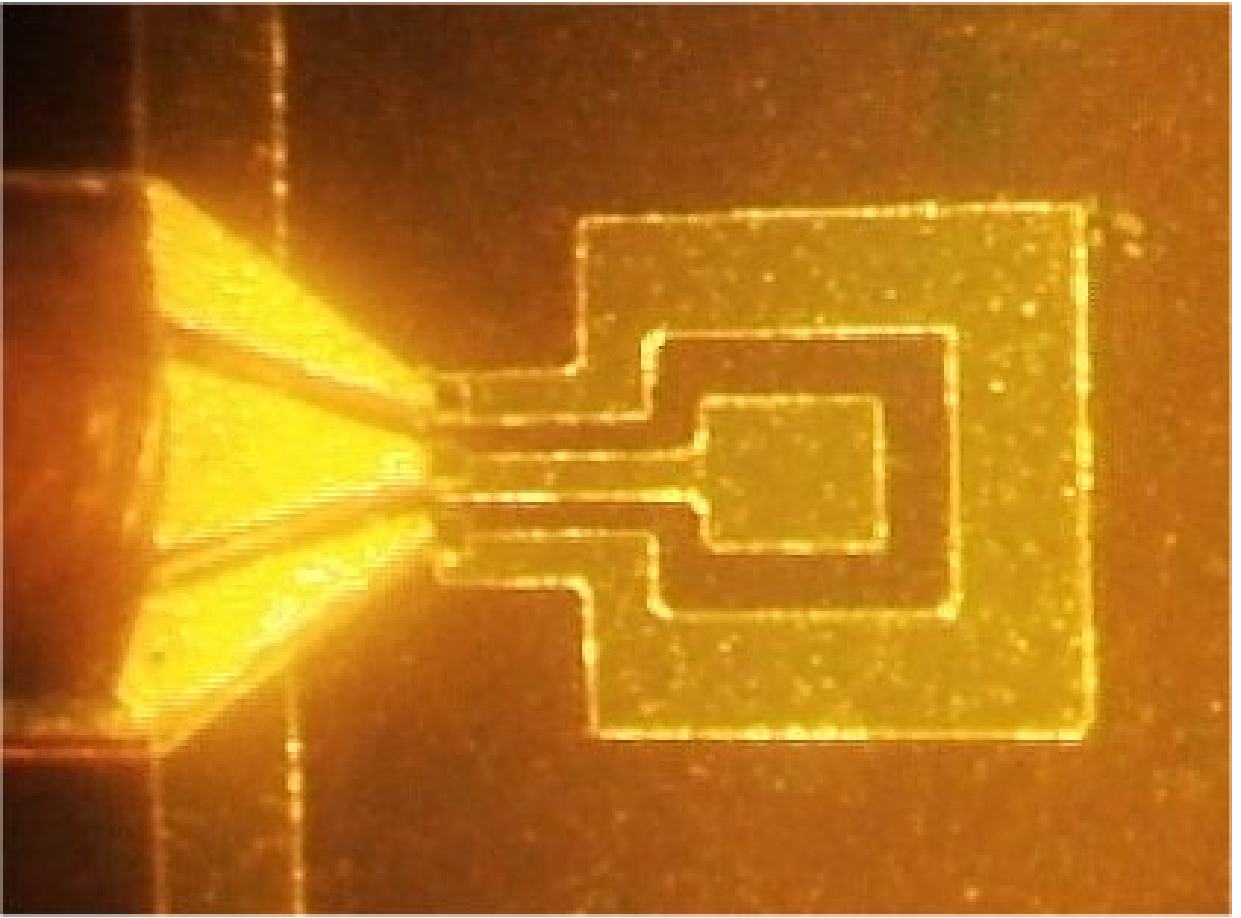
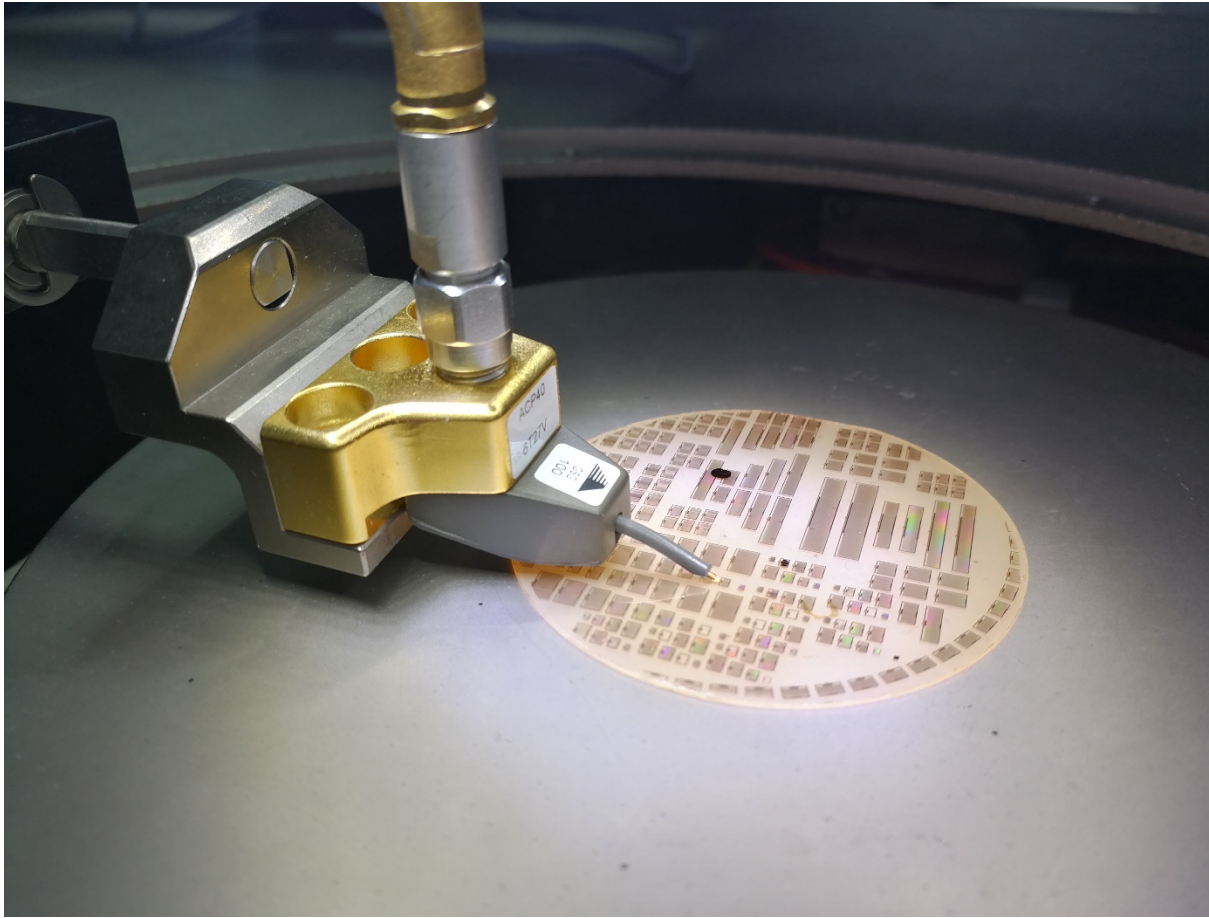
SAW 滴光刻胶



[-]俯视图二维线图

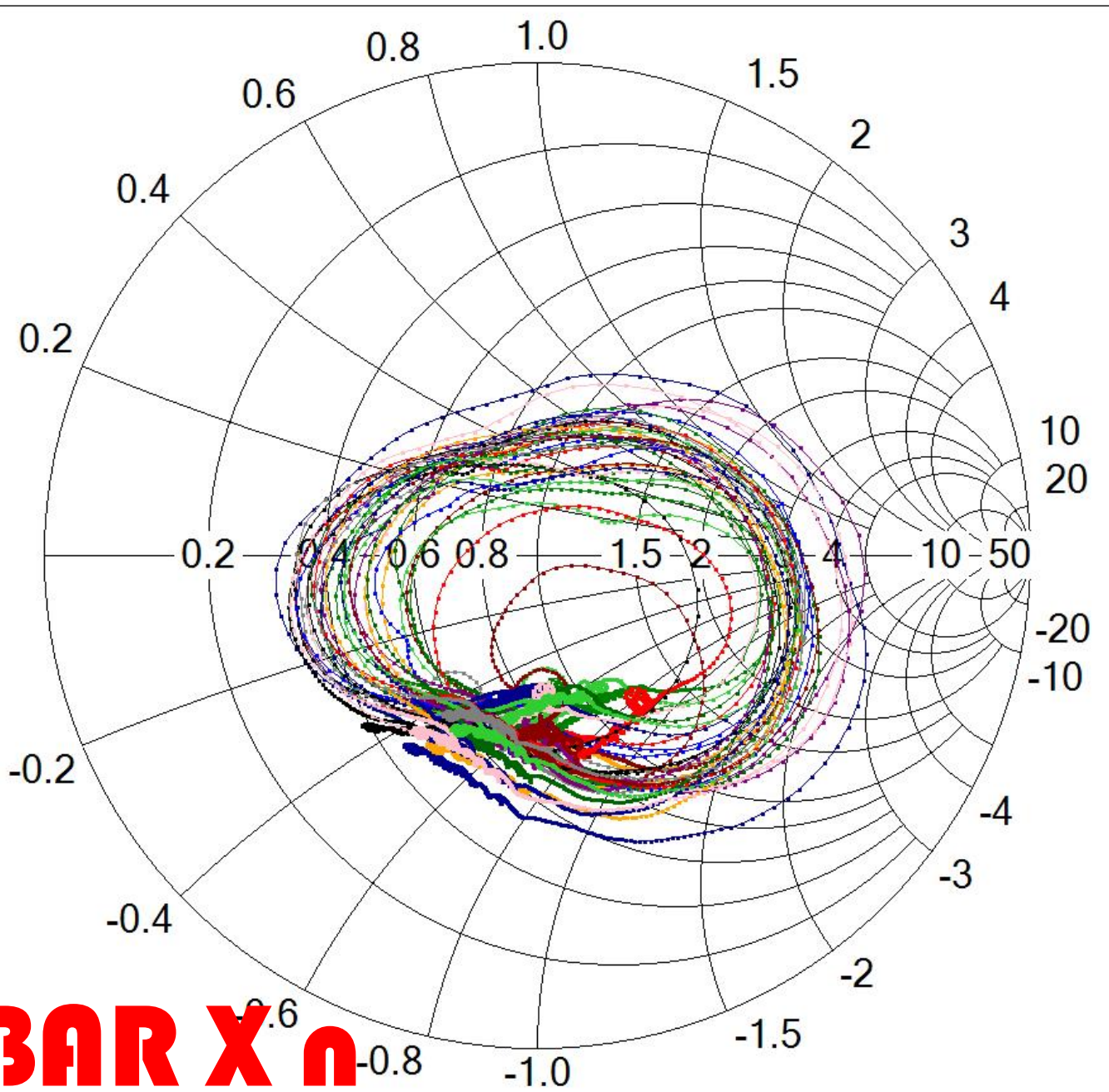


FBARs & SAWs

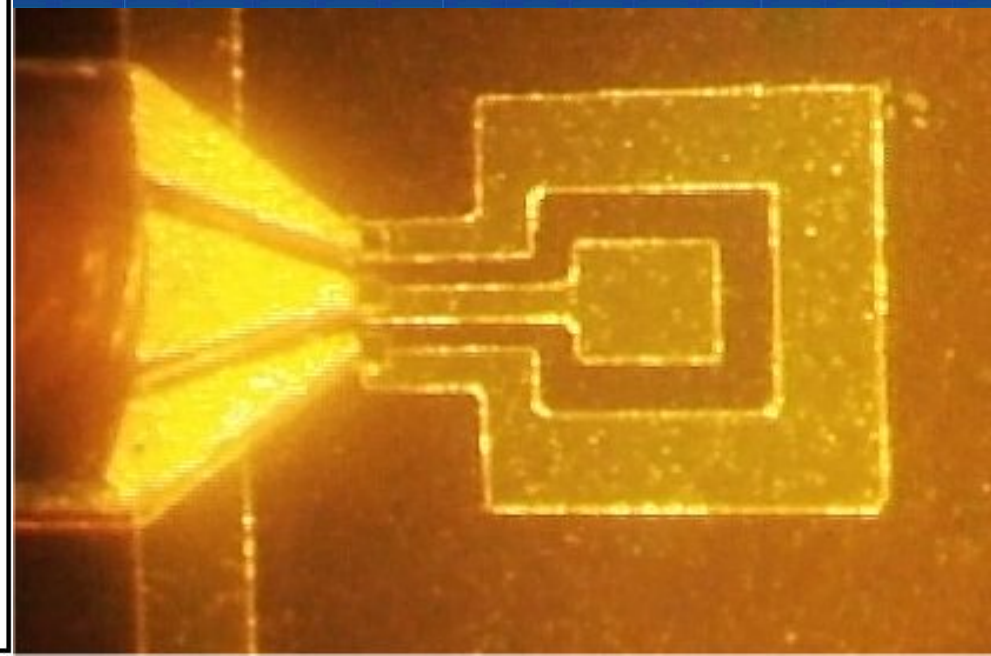
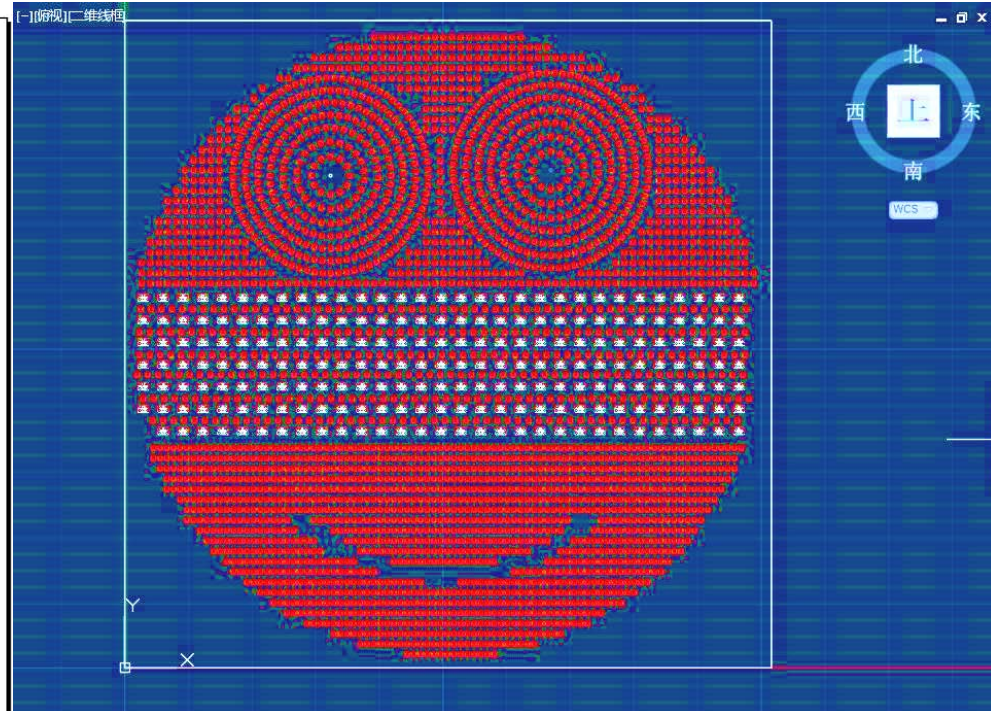


# RF Probing





**FBAR X n**





上海交通大学

SHANGHAI JIAO TONG UNIVERSITY

# 上海交通大学薄膜高温温度传感器在 航空发动机测温方面的应用成果简介

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电子邮箱：[franklinduan@sjtu.edu.cn](mailto:franklinduan@sjtu.edu.cn)





# 薄膜高温温度传感器



What 做了什么？

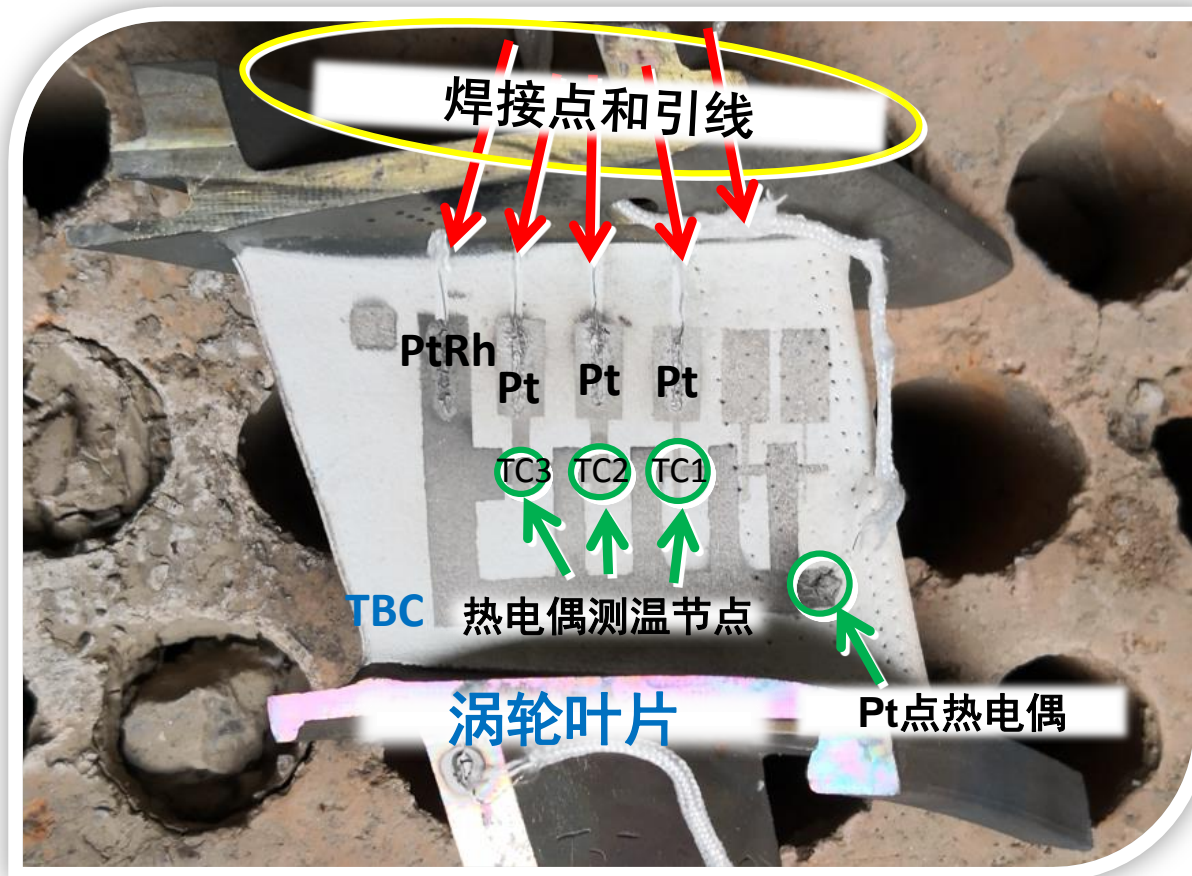


Why 可以用在哪？



How 具体的一些例证。

## What - 我们做了什么？



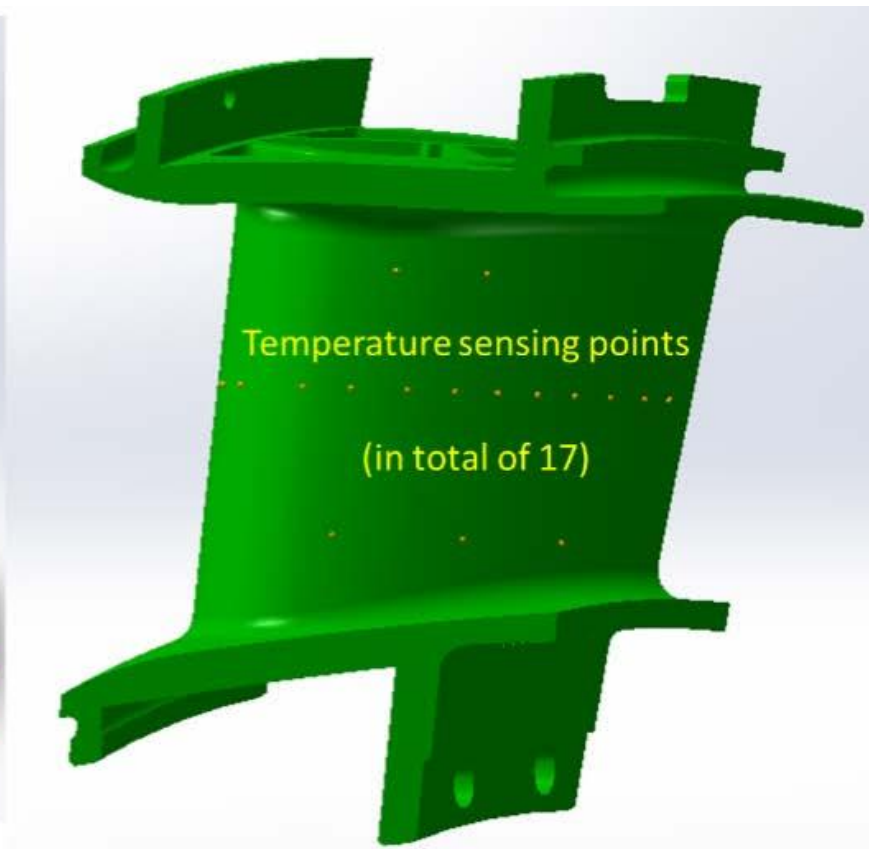
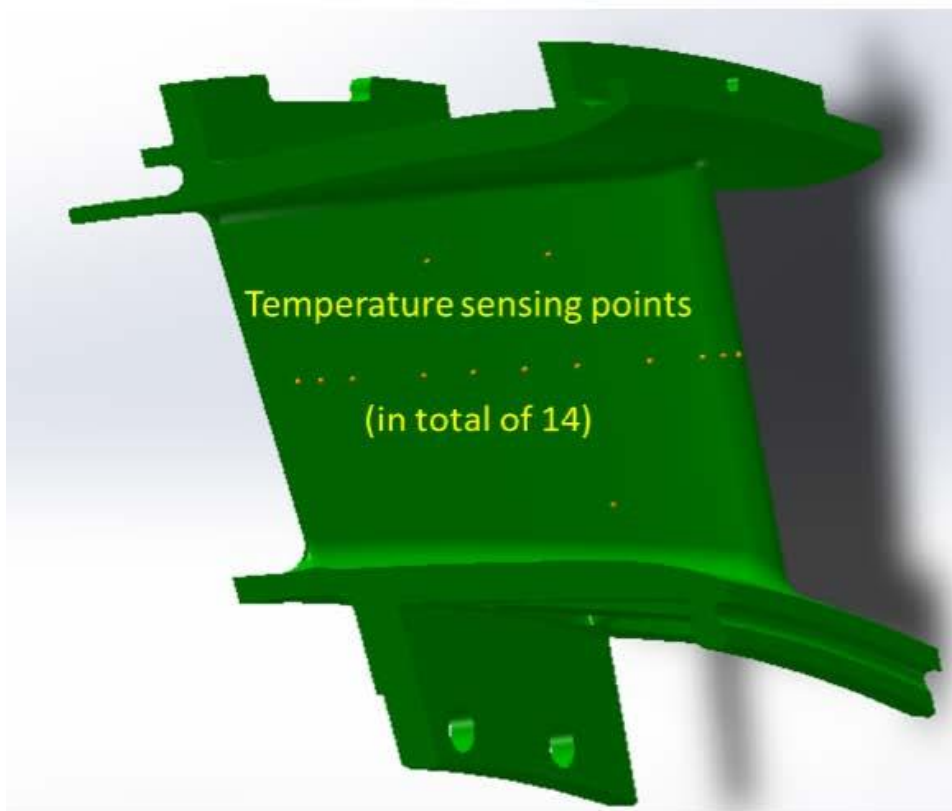
用MEMS技术在叶片表面原位集成的薄膜热电偶阵列



## What - 关键指标

- ④ Pt/PtRh薄膜热电偶，测温高达1600°C (CMC)
  - 工程实用性强
  - 叶片曲表面TBC上原位集成制作
  - 抗振动（40g）冲击（100g）、抗温度冲击、航发燃动环境测试
  - 重复性与稳定性好、误差小（3%）

## Why — 航空发动机的智能化 & 聪明的传感器。



C919 → 航空发动机 → 温度 → 传感器



## Why - 可能应用点?

- ④ 航发涡轮冷效实验
- ④ 热障涂层隔热温度表征测量
- ④ CMC, SiC等材料表面温度测量 (1600°C)
- ④ 涡轮叶片表面温度分布
- ④ 表面温度动态瞬态测量

# How 我们的成果

⑥ 论文/会议：2016~2019

⑥ 下几页的内容 .....

## 2018 (论文/会议)

1. Duan Franklin Li, Hu M, Zou B, et al. An Easy Way of High-Temperature Monitoring of Aero-engine Blade Surface for Intelligent Propulsion Systems[C]// Joint Propulsion Conference. 2018.
2. Franklin L. Duan, Mingkai Hu, Yuzhen Lin, Jibao Li, and Xueqiang Cao. "A New High-Temperature Sensing Device by Making Use of IBC Thermistor for Intelligent Propulsion Systems". 2018 AIAA/IEEE Electric Aircraft Technologies Symposium, AIAA Propulsion and Energy Forum, (AIAA 2018-5015) <https://doi.org/10.2514/6.2018-5015>
3. Franklin L. Duan and Yuzhen Lin. "Development of Accurate and Robust High Temperature Sensor on Aero-engine Turbine Blade Surface". 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4622). <https://doi.org/10.2514/6.2018-4622>
4. 段力, 高均超, 丁桂甫, 邵峰, 毛成龙, 沈杰, 静波. 航空发动机涡轮叶片原位集成高温MEMS传感器的研制 《航空发动机》, 2018, 44(4):56-60
5. Mingkai Hu, Franklin Li Duan, Design and characterization of SAW devices on LiNbO3 bulk and ZnO thin film substrates. Solid-State Electronics, 2018, 167: 28-34. ISSN 0038-1101. <https://doi.org/10.1016/j.sse.2018.05.001>
6. Yijian Liu, Zhongli Li, Zhi Yan, Yuzhen Lin, Yuzhen Lin, Zhang, Huey-liang Hwang, Franklin Duan\*\*, Yafei Zhang\*. Novel design and performance of the high-temperature sensor with an AlN-buffered ZnO piezoelectric film [J]. Vacuum, 154 (2018) 11-17.
7. Franklin Li Duan, Jibao Li, Junchao Gao, Chang Yu, Wentao Ma, Yuzhen Lin, and Xueqiang Cao. "Integrated Fabrication of High-Temperature Microelectromechanical System Sensor on Aero-engine Turbine Blade", Journal of Thermophysics and Heat Transfer, Vol. 32, No. 3 (2018), pp. 828-830. <https://doi.org/10.2514/6.2018-115147>

## 2016、17 (论文/会议)

1. Franklin L. Duan, etc. "High Temperature Sensors for Intelligent Aero-Engine Applications", 33rd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, (2017), AIAA AVIATION Forum, <https://doi.org/10.2514/6.2017-3239>
2. 段力, 高均超, 汪瑞军, 明铭楷, 苏靖超, & 成清涛等. (2017). 航空发动机叶片表面热障涂层温度分布的仿真分析. 《上海交通大学学报》57(8), 915-920.
3. 李磊, 段力, 秦格华, 马腾川, 王云生, & 陶闻钟等. (2017). 应用于航空发动机涡轮叶片的热障涂层材料研究. 《功能材料》48 (2), 2084-2090.
4. 明铭楷, 翁昊天, 刘骏尘, 付学成, 史丽云, 丁桂甫, 张亚新, 段力. "设计和工艺参数对声表面波器件性能的影响" 《微纳电子技术》, (2017), 54(11):752-759.
5. 高均超, 段力, 王奕, 刘明, 王凤丹, 丁桂甫, 汪红, 程涛, 吴帆峰, 王强, 郑芳芳, 邵峰, 谢开成, PDMS软质模板制备与叶片曲面图形转移工艺, 《微纳电子技术》, (2016)
6. Junchao Gao, Franklin Li Duan, Chang Yu, Wentao Ma, Yuzhen Lin, Guifu Ding, Congchun Zhang, Ying Wang. Electrical insulation of ceramic thin film on metallic aero-engine blade for high temperature sensor applications. Ceramics International, Volume 42, Issue 16, December 2016, Pages 19269-19275, ISSN 0272-8842. <http://dx.doi.org/10.1016/j.ceramint.2016.09.093>

1. Franklin L. Duan (通讯作者), Ji, Zhonglin, Haotian Weng, etc. "Study of Electrical Protection Coating under High Temperatures for Aero-engine Smart Sensors", AIAA Propulsion and Energy 2019, Indianapolis, USA, <https://arc.aiaa.org/doi/10.2514/6.2019-4087>
2. Haotian Weng, Franklin L. Duan (通讯作者), "High Temperature Wireless Sensing on Aeroengine", AIAA Propulsion and Energy 2019 Forum, 19-22 August 2019, Indianapolis, USA, <https://arc.aiaa.org/doi/10.2514/6.2019-4085>
3. Ji, Zhonglin, Duan, Franklin Li (通讯作者), "Temperature Distribution Measurements on Turf of Simple Dotted Pt/PtRh Thermal Couple Test Array", AIAA Propulsion and Energy 2019 Forum, Indianapolis, USA, <https://arc.aiaa.org/doi/10.2514/6.2019-4084>
4. Franklin L. Duan (通讯作者), Haotian Weng, etc. "Robust Thin Film Temperature Sensors on Turf Surface", AIAA Journal, 2019, (12).
5. H. Weng, F. L. Duan (通讯作者), Y. Zhang and M. Hu, "High Temperature SAW Sensors on LiNbO3 Passivation Layer", AIAA Journal, 27 August 2019, <https://ieeexplore.ieee.org/abstract/document/8711717/i.issn1671-833x.2019.17.0812019>
6. 段力, 短中林, 翁昊天, 丁桂甫, "热障涂层导电性能研究", 航空制造技术, 2019, Issue (17): 81-84. <http://www.cmaa.org.cn/journal/1001-7047/j.issn1671-833x.2019.17.0812019>
7. Haotian Weng, Franklin Li Duan (通讯作者), etc. "Electrical Insulation Improvements of Ceramic Thin Film on Aeroengine Turbine Blade", Ceramics International, Oct. 2019
8. 段力, 翁昊天, 丁桂甫, 王益, "精确测量热障涂层温度隔离高效能方法探究 - 双层MEMS薄膜", 航空发动机, 2019, 44(4):56-60
9. 短中林, 段力, 翁昊天, 丁桂甫, "利用原位集成热电偶技术精准测量涡轮叶片表面高温温度新方法", 航空发动机, 2019, 44(4):56-60
10. Franklin Li Duan (通讯作者), Zhi Yang, Zhonglin Ji, Haotian Weng, Ziyi Xie, Allegro Shen, Chen Qianhui Liu. Process optimization and device variation of Mg-doped ZnO FBARs. Solid-State Electronics, 2019, Pages 11-17, ISSN 0038-1101.
11. 陈熙, 段力 (通讯作者), 等, 氧化锌薄膜体声波谐振器制作重复性和均匀性 [J]. 微纳电子技术, 2019, 56(11):752-759.

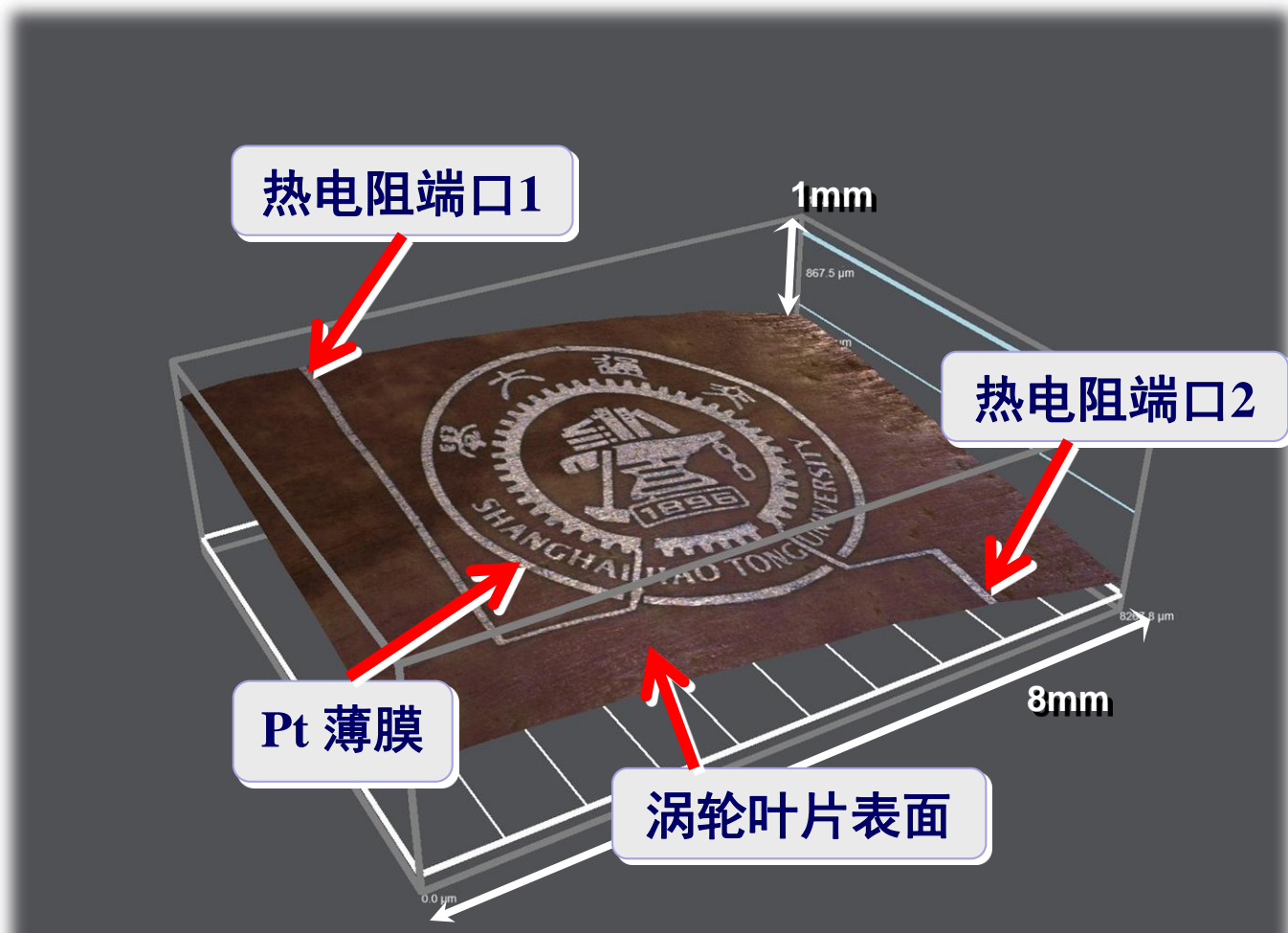
11

7

6



## 原位3D集成技术



3D 原位集成在叶片表面的Pt薄膜 (0.001mm厚)

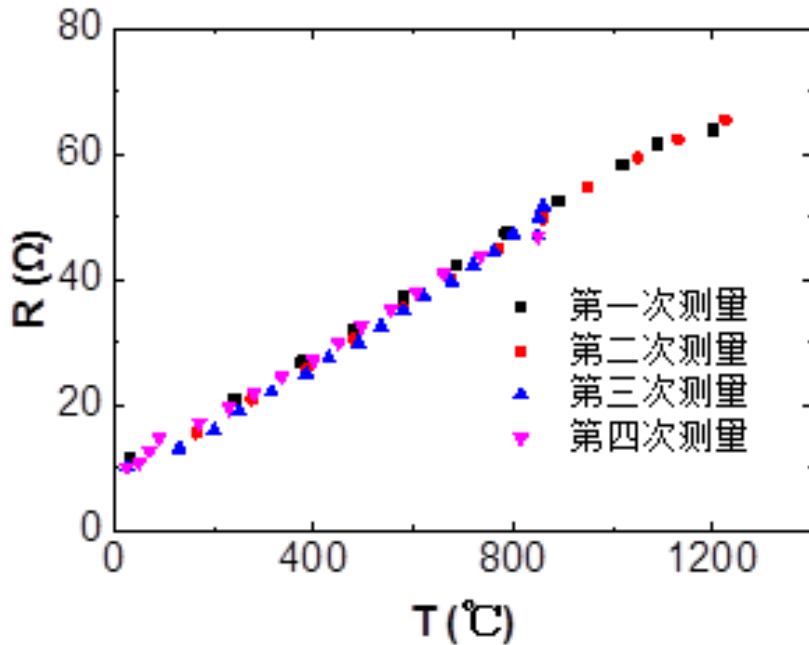
## 涡轮叶片表面原位集成的薄膜传感器



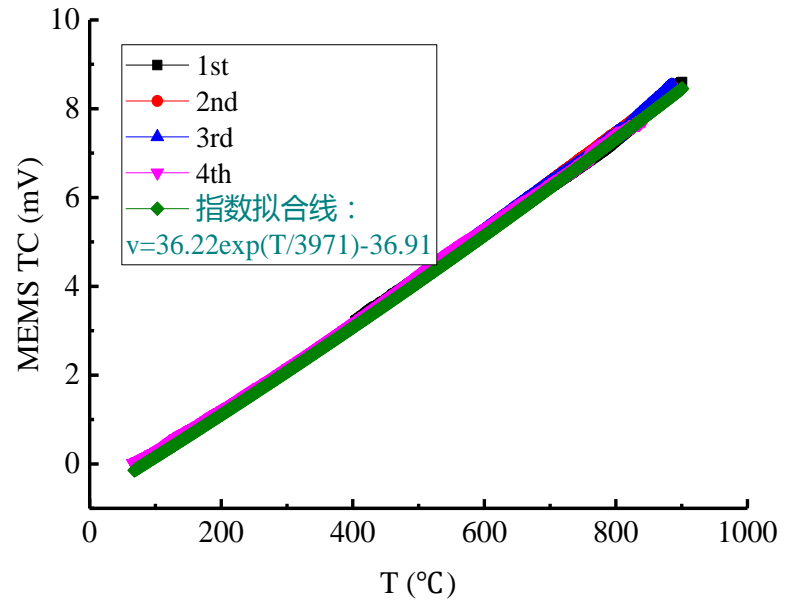
涡轮一导叶片表面原位集成的MEMS薄膜热电偶与薄膜热电阻温度传感器。交大校徽也是一个薄膜型的Pt/PtRh热电偶。



# 温度传感测量结果

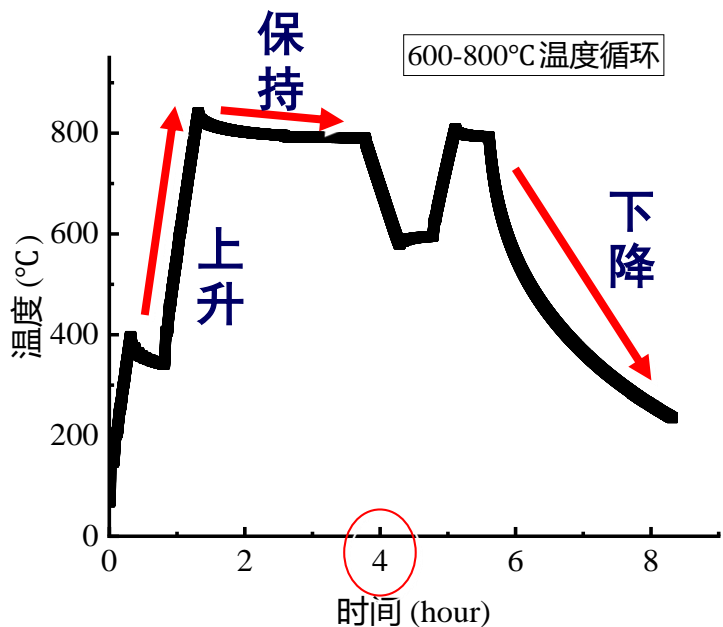


薄膜热电阻传感器RTD  
(4次的测量结果)



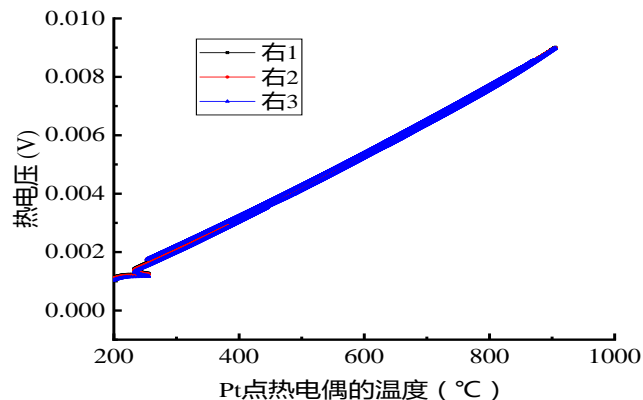
薄膜热电偶传感器TC  
(4次的测量结果)

# 重复性、稳定性与测量误差

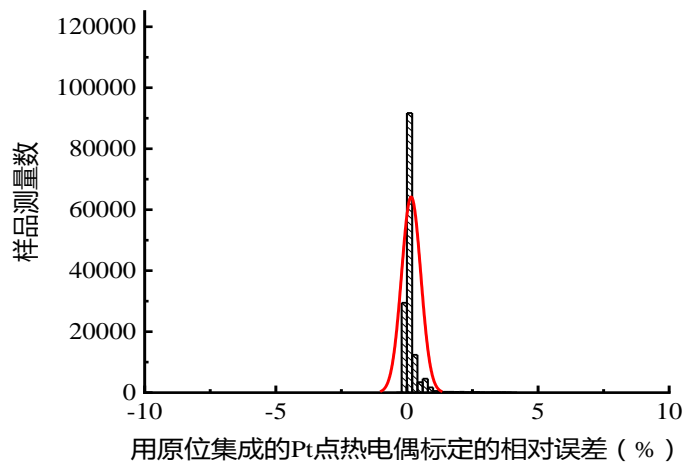


温度上升、下降、保持的变化曲线

**重复性:** 指的是多次测量与升温降温过程薄膜传感器测温曲线的重合性。  
**稳定性:** 指的4个小时的长时间温度状态下薄膜传感器特性是否有漂移。  
**测温误差:** 指的是把所有的测量点与平均值之间的数据差异做正态分布处理从而比较出整体的统计误差。



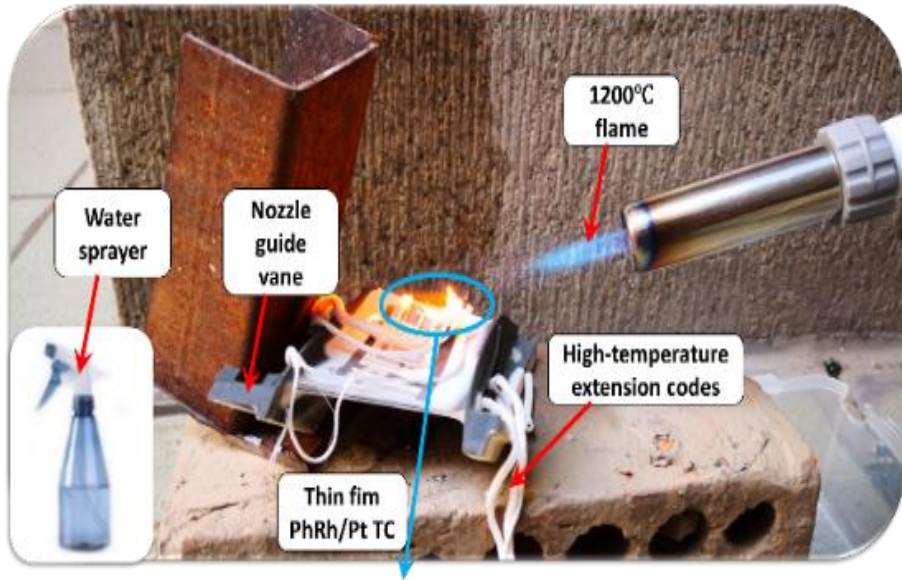
测量重复性与稳定性  
(100,000测量点; 20-800°C 温度循环)



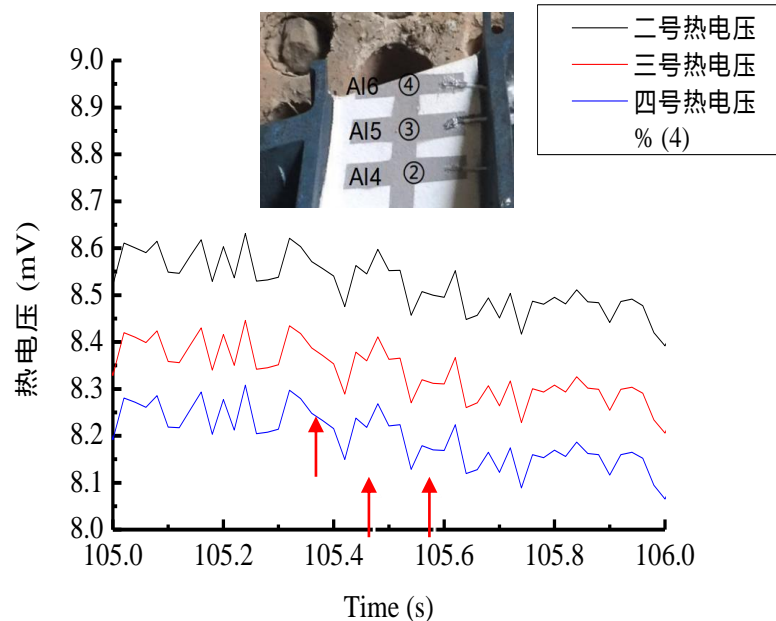
测温误差 <3%



# 瞬态温度分布测量

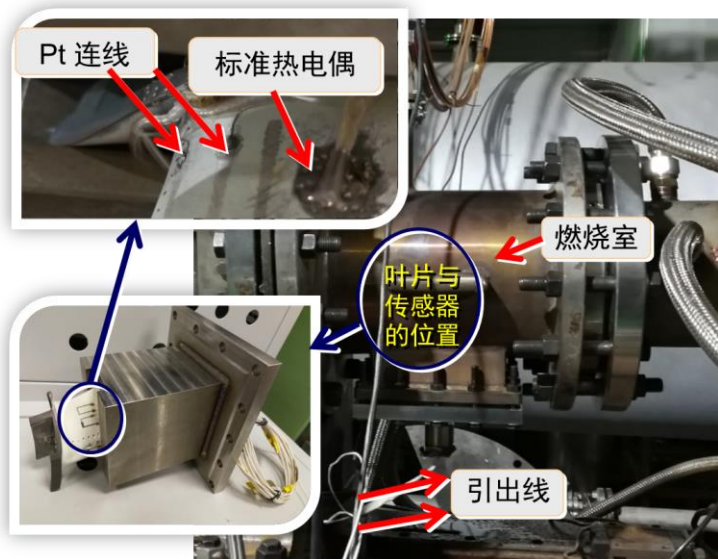


**实验：**叶片表面传感器阵列测量温度分布实验。离火源近的地方温度要稍微高一些，对应的传感器的热电压也要高一些。高温实验之后用喷水枪进行骤然冷却，用来检验TBC与薄膜传感器连接强度。



**结果：**薄膜热电偶对温度变化的反应速度，三个薄膜热电偶对于温度的细小变化**有一致（同时高、同时低。）**的反应，动态反应效应效果很好。

# 传感器在航空发动机燃动环境下的热流实验



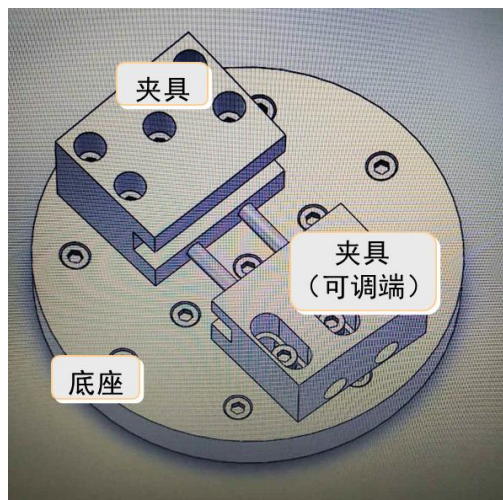
高温温度传感器在燃烧室中的安装与高温连线图

- 测试条件：流量0.5Kg/s，热流量1.24L.J/K.K，温度1200°C，燃气压力0.5MPa，流速51-56m/s

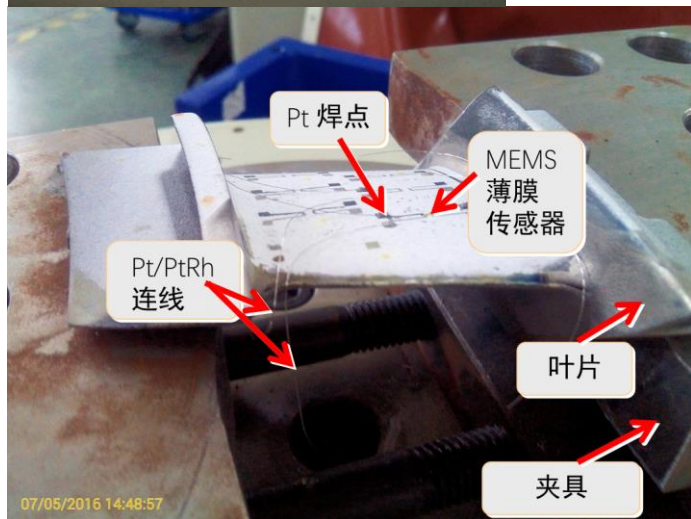
		状态1	状态2	状态3	状态4
空气流量	kg/s	0.5	0.5	0.5	0.5
进口空气温度	K	550	550	600	643
油气比	-	0.008	0.014	0.0185	0.024
燃气压力	MPa	0.5	0.5	0.5	0.5
理论燃气温度	K	861	1083	1268	1476
燃气密度	kg/m <sup>3</sup>	2.023415	1.608643	1.373943	1.180325
燃气比热	kJ/(kg·K)	1.1267	1.1859	1.2295	1.2895
通道面积	m <sup>2</sup>	0.007854	0.007854	0.007854	0.007854
流速	m/s	31.46264	39.57496	46.33522	53.93596
热通量					



# 振动与冲击实验



振动冲击台的  
夹具和安装在  
台上的叶片与  
传感器及其金  
属连线



振动 冲击 试验台

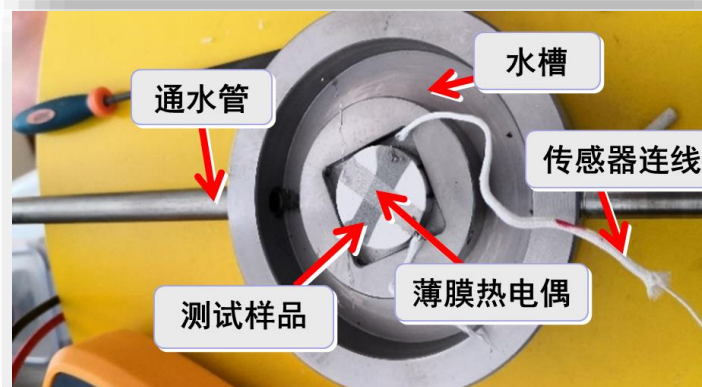
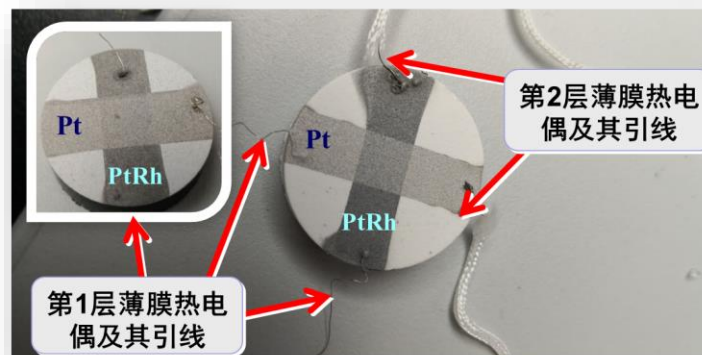
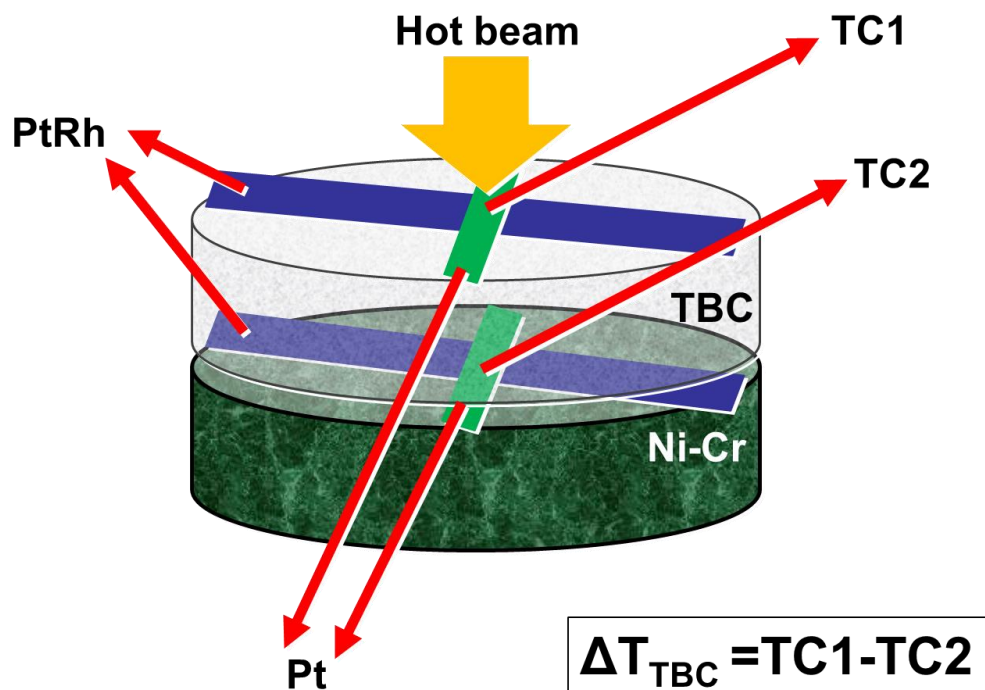
# 火焰喷射实验



测量温度分布与瞬态反应及其骤然冷却效果

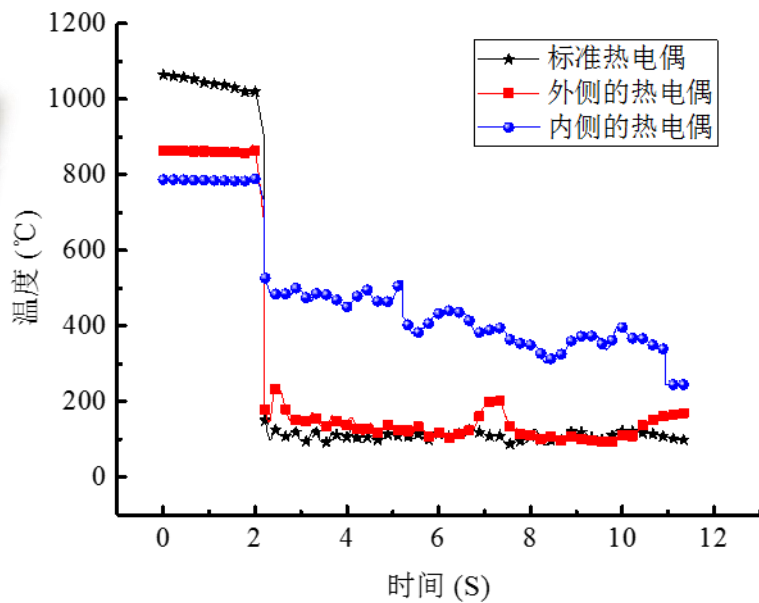
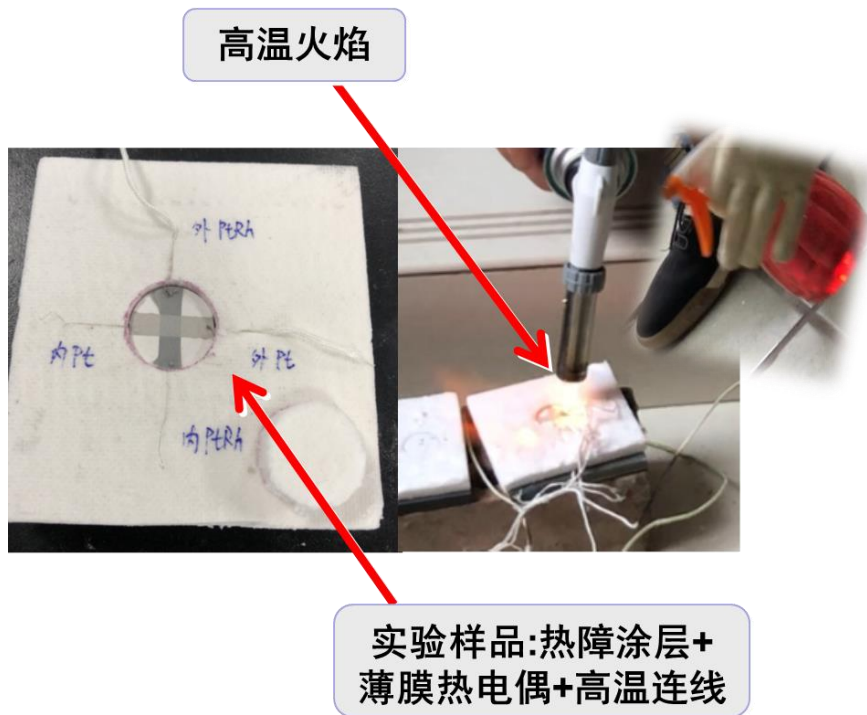


# 利用双层薄膜传感器对TBC隔热性能测量



利用两个薄膜热电偶 ( TC ) 测量热障涂层 ( TBC ) 的隔热能力

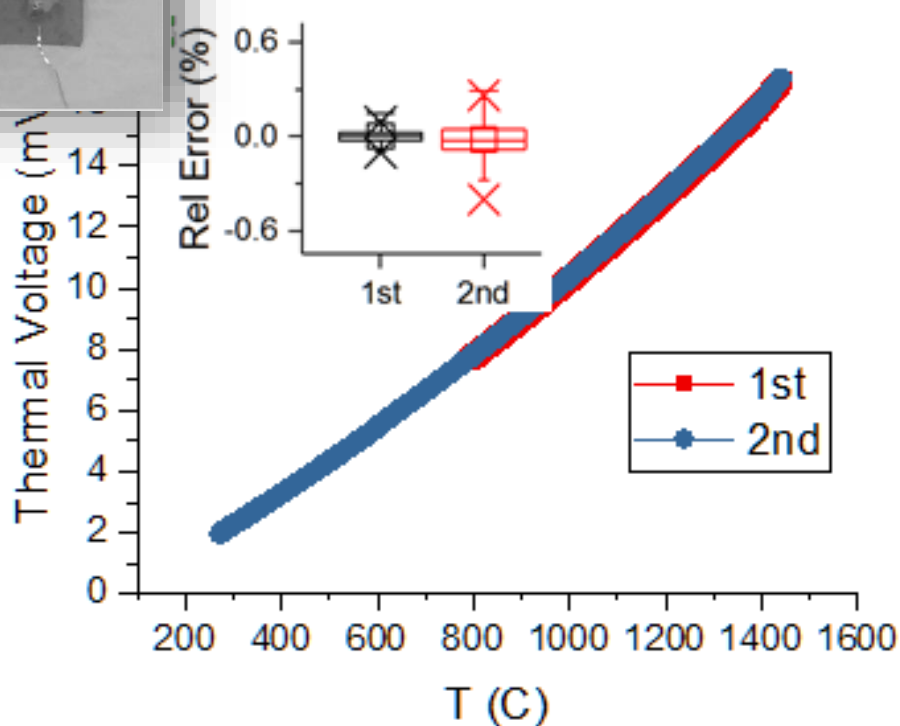
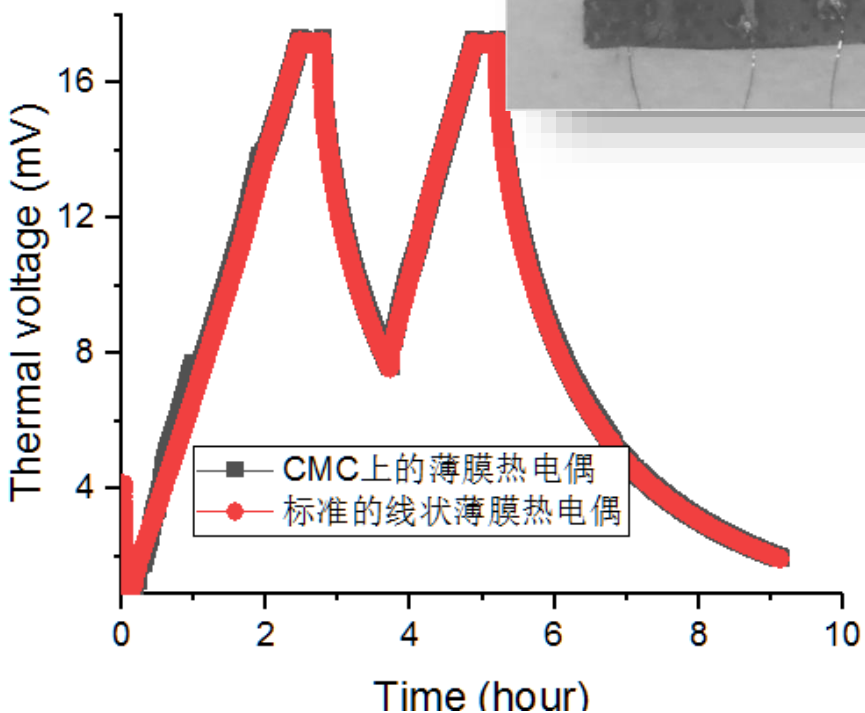
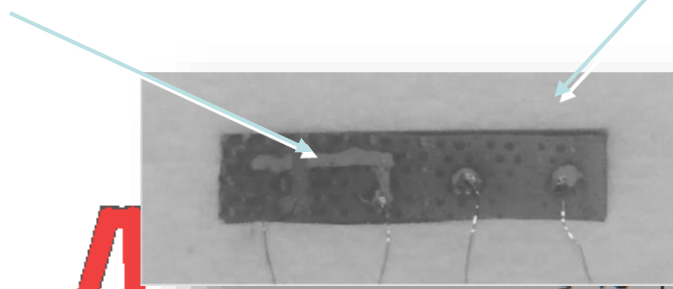
# 热障涂层隔热效果实验



先给表面的热障涂层 ( TBC ) 加热, 然后用喷水枪骤然水冷, 然后高速数据采集TBC两侧的温度算出温度差。



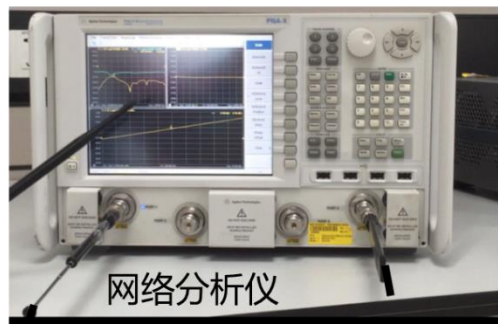
# Pt/PtRh薄膜热电偶, CMC 1600°C 测温结果



将近10个小时的温度循环  
(1mV~100°C)

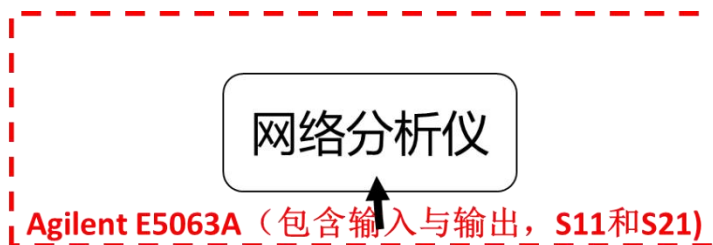
相对误差在3%之内  
(1mV~100°C)

# 无线无源高温传感技术



SAW与集成天线

实际测量系统



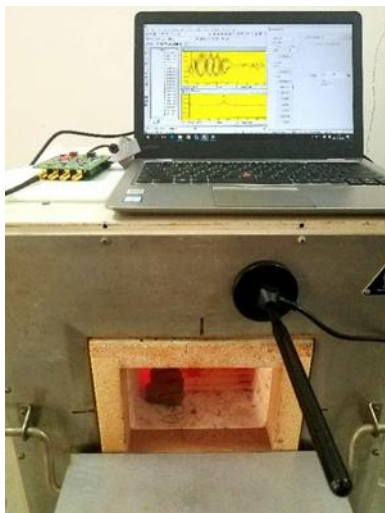
测量结构示意图

**Challenge: RF + 1100°C !**

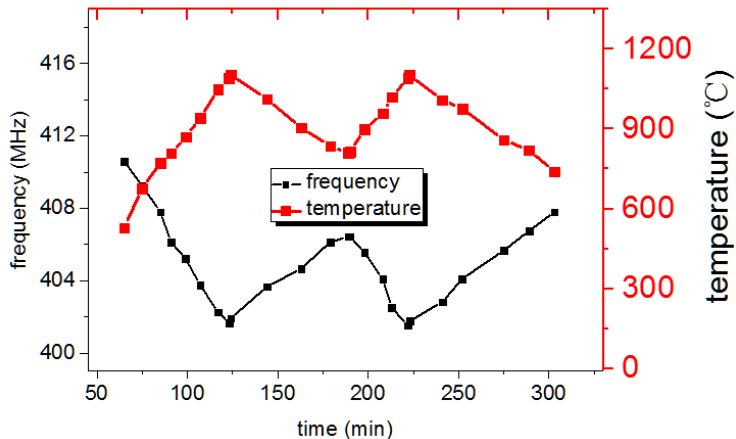
# 无线无源高温传感研发的部分结果



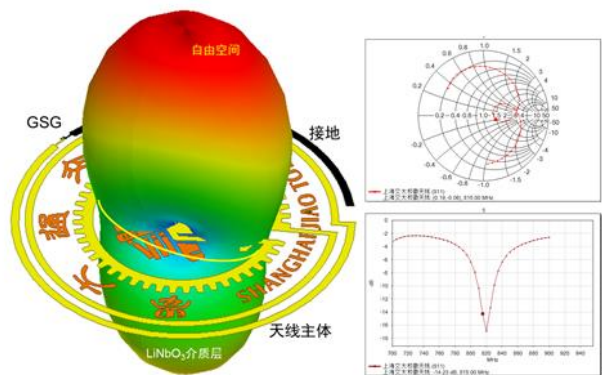
航空发动机涡轮叶片表面TBC上制作的近场天线与SAW



高温RF测量体系



SAW的 $f_0$  vs. 温度，六个小时温度循环测量，测量相对误差 $<3\%$



近场天线方向图（使用交大校徽改制成的环形天线）以及史密斯图阻抗与S11频率特性



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# Summary

- ④ What: Pt/PtRh薄膜热电偶, 测温高达1600°C, 工程实用性强
  - 叶片表面TBC上原位集成制作
  - 抗振动(40g)冲击(100g), 温度冲击实验(温振), 航发燃动环境测试
  - 重复性与稳定性好、误差小(3%)
- ④ Why: 叶片表面、其他材料表征方面、高温温度测量
  - 航发涡轮冷效实验
  - 热障涂层隔热温度表征测量
  - CMC, SiC等材料表面温度测量
  - 涡轮叶片表面温度分布
  - 表面温度动态瞬态测量
- ④ How
  - 课题组发表的文章、会议: 2016~2019