Fraunhofer IZM
Fraunhofer Institute for Reliability and Microintegration IZM

Packaging and Interconnection Technologies for Bioelectronics
Prof. Vasiliki Giagka

Electronic Packaging Days 2025

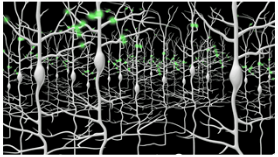
Soft Medical-Grade Substrates for Neural Interfaces

Bioelectronic medicine to treat neurological disorders

Neurological disorders is the leading cause of disability worldwide

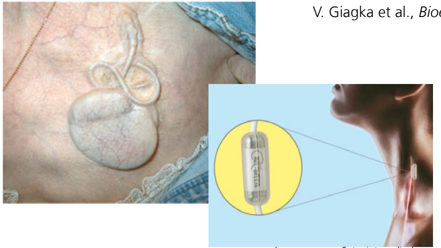
epilepsy, depression,
chronic headache,
rheumatoid arthritis,
diabetes…

- **We need a better understanding of how our nervous system works**



- **Current technology is limiting**
  - highly invasive
  - environment hostile to electronics
  - resolution is low

V. Giagka et al., *Bioelectr. Med. 2018*



Images source: Setpoint medical

Technology needs: We need **smaller, robust and more precise** active neural interfaces

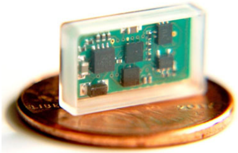
Packaging for long-term active implants

1st Gen.

Conventional
Vagus nerve stimulator

2nd Gen.

Advanced
Glass-housed VNS

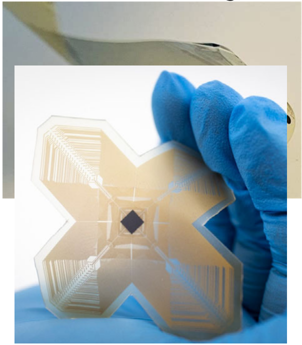


TxBDC TEXAS BIOMEDICAL DEVICE CENTER

MOTIF NEUROTECH

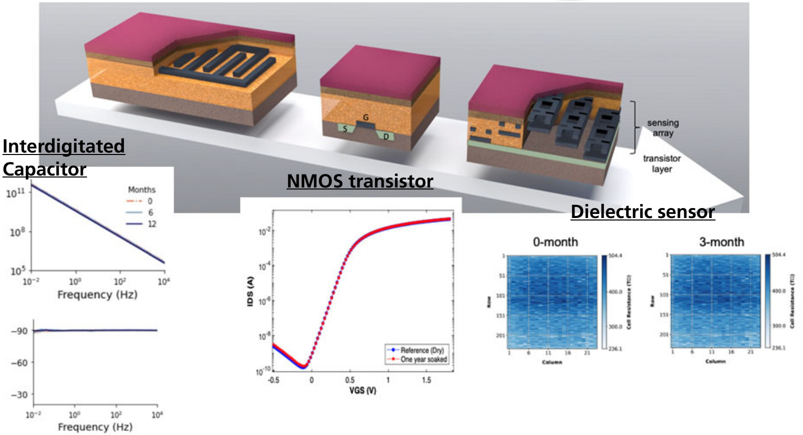
3rd Gen.

Conformal coating

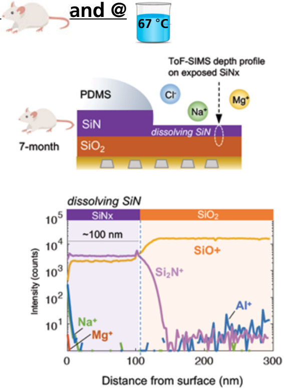


Silicon ICs are themselves “hermetic”

Electrical performance of standard CMOS stable after 1 year @ 67 °C, 0/5/15 V



CMOS passivation blocks ion (and moisture*) penetration in and @ 67 °C

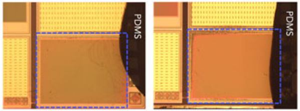


K. Nanbakhsh et al., *Nat. Commun. 2025*

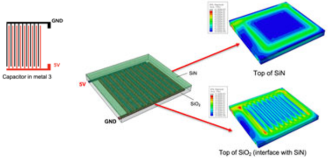
CMOS passivation degrades in wet ionic environments

Degradation is stress signal dependent

On the chip: Local SiN degradation due to electric field + adsorbed ions



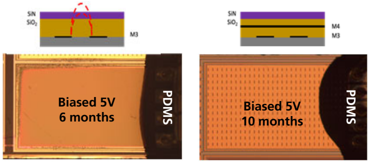
Not biased Biased with 5V



Shielding and AC electric fields lead to longer lifetimes

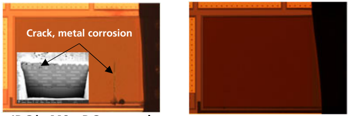
Shielding

AC/DC



Non-shielded IDC
Local degradation after 6 months

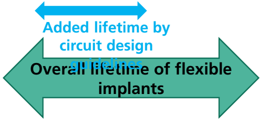
Shielded IDC
No change after 10 months



IDC in M6 – DC stressed
Failure after 2 weeks

IDC in M6 – AC stressed
No failure after 6 months

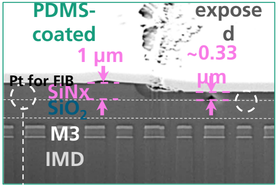
IC design for conformal encapsulation



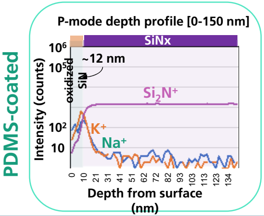
K. Nanbakhsh et al., *Nat. Commun. 2025*

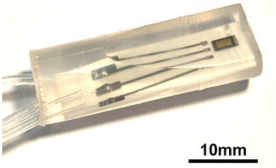
PDMS-coatings as permeable but reliable packaging

PDMS prevents SiN dissolution



PDMS prevents ion ingress





Silicone-coated ICs intact after 4.3 years @67℃, 5V DC

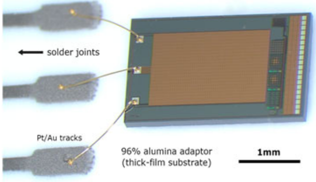
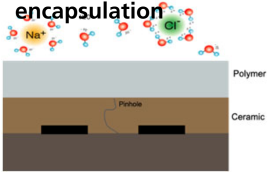


image taken through transparent MED-6015 silicone

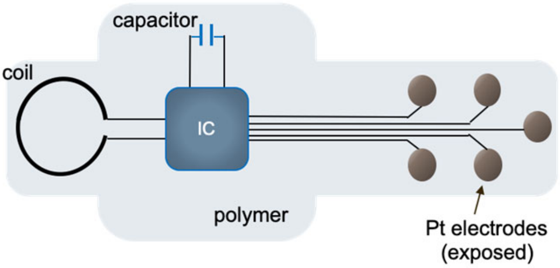
Polymeric encapsulation



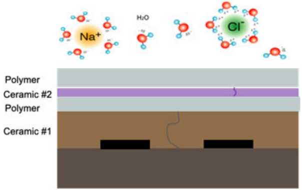
ensuring adhesion on top of hermetic components

A. Shah Idil et al., *bioRxiv 2025*
K. Nanbakhsh et al., *Nat. Commun. 2025*

Not all components will be “inherently hermetic”



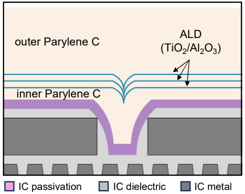
Thin-film packaging

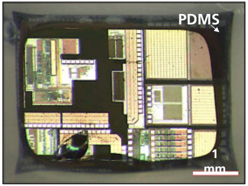


moisture barriers / multistacking

Organic-inorganic and nanolaminate multilayers for thin-film packaging

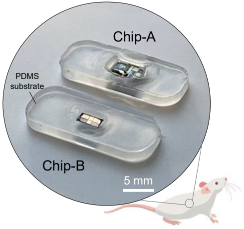
6 µm ParC-ALD-ML (TiO_2/Al_2O_3)



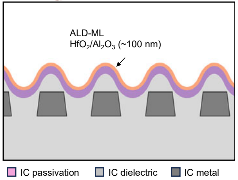


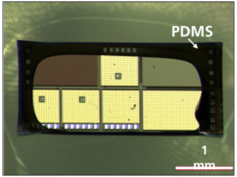
No visible degradation
No Al pad corrosion

7 months in vivo



100 nm ALD-ML (HfO_2/Al_2O_3)



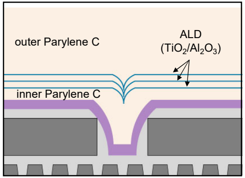


K. Nanbakhsh et al., *Small 2025*

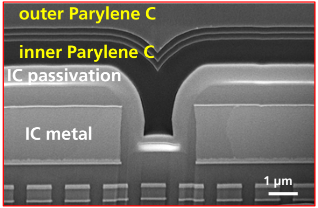
K. Nanbakhsh et al., *Small 2025*

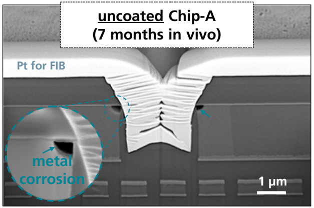
Thin-film multilayers – in vivo stability

6 µm ParC-ALD-ML (TiO_2/Al_2O_3)



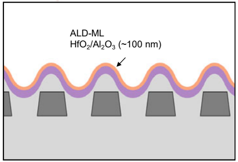
IC passivation IC dielectric IC metal



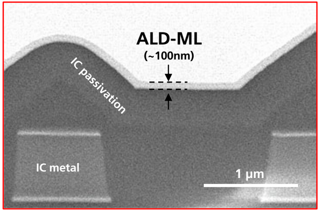


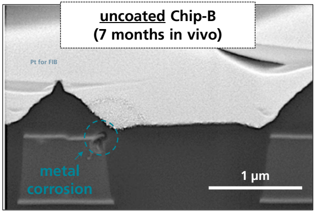
Structural stack stability
Coverage of complex topographies
Protection of chip passivation degradation and metal corrosion

100 nm ALD-ML (HfO_2/Al_2O_3)



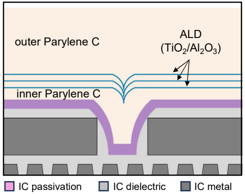
IC passivation IC dielectric IC metal

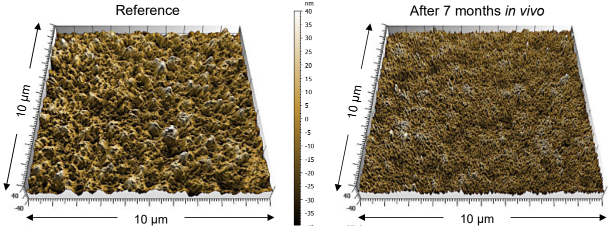




Thin-film multilayers – in vivo stability

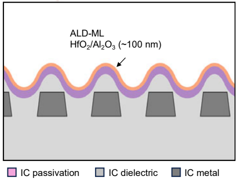
6 µm ParC-ALD-ML (TiO_2/Al_2O_3)

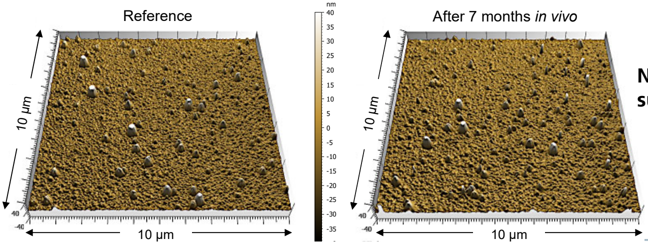




Surface nano-roughening of Parylene

100 nm ALD-ML (HfO_2/Al_2O_3)

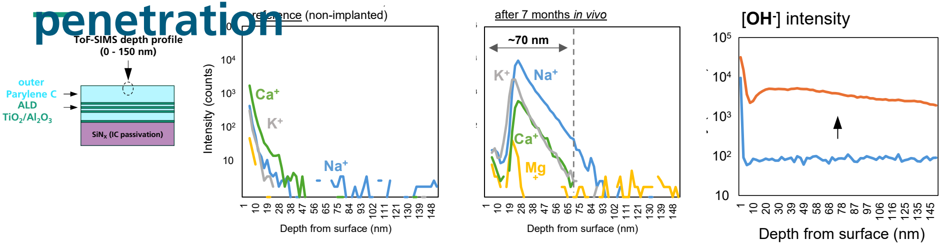




No visible change in surface topography

K. Nanbakhsh et al., *Small 2025*

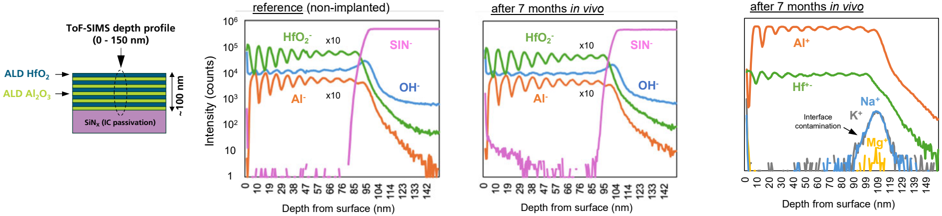
Thin-film multilayers – ion and moisture penetration



Organic-inorganic

Surface degradation (~70 nm) Parylene

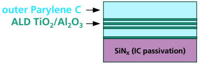
- **Ion penetration**
- **Moisture penetration**



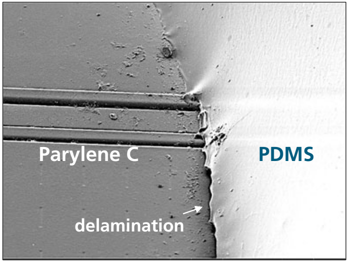
ALD nanolaminate

No ions
No moisture

Adhesion to PDMS

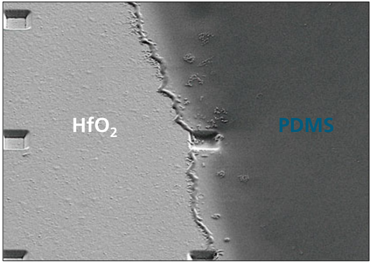


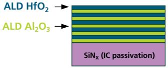
Organic-inorganic



Delaminatio
n

ALD nanolaminate





Strong

Silicone is a great substrate for soft implants

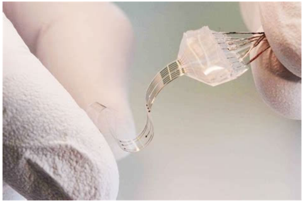


Photo © EPFL, Minev et al., Science, 2015

CorTec

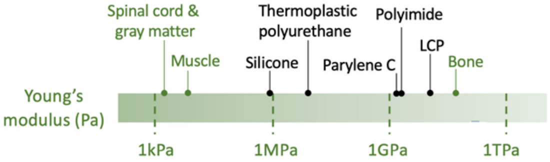
Neurosoft

But is not easily compatible with microfabrication techniques

- **Limits resolution**
- **Limits use with advanced assembly and packaging techniques**

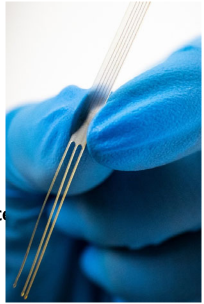
A. Pak et al., *in preparation*
A. Velea et al., *IEEE EMPC 2020*

Thermoplastic polyurethane as a substrate and coating for neural interfaces



PU as a substrate for active neural implants

- **Soft**
- **Medical grade**
- **Thermoplastic → excellent adhesion due to lamination → increased lifetime**
- **Compatible with microfabrication → high density neural interface**



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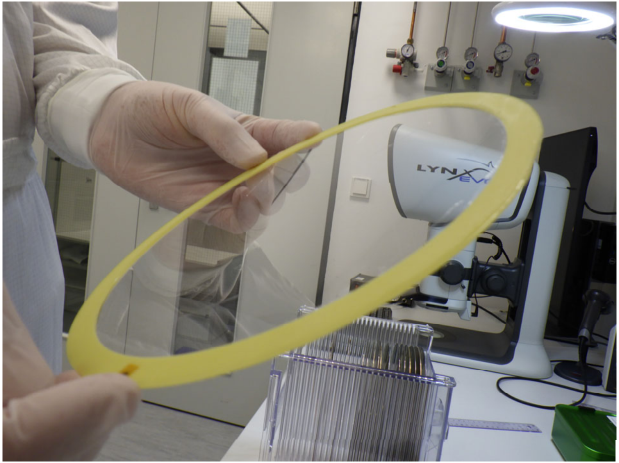
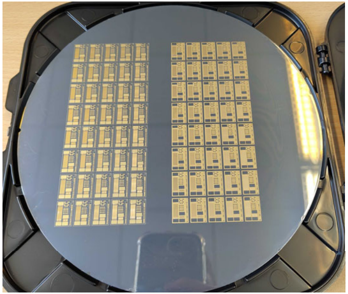
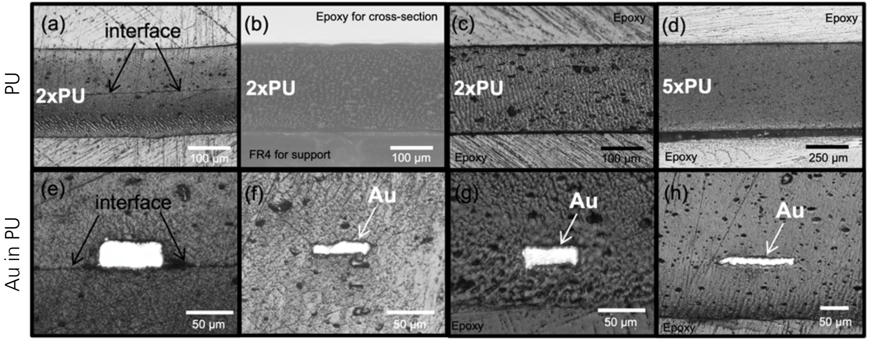
Wafer level fabrication with medical grade TPU



- **3 µm film**



Thermoplastic polyurethane as a substrate and coating for neural interfaces



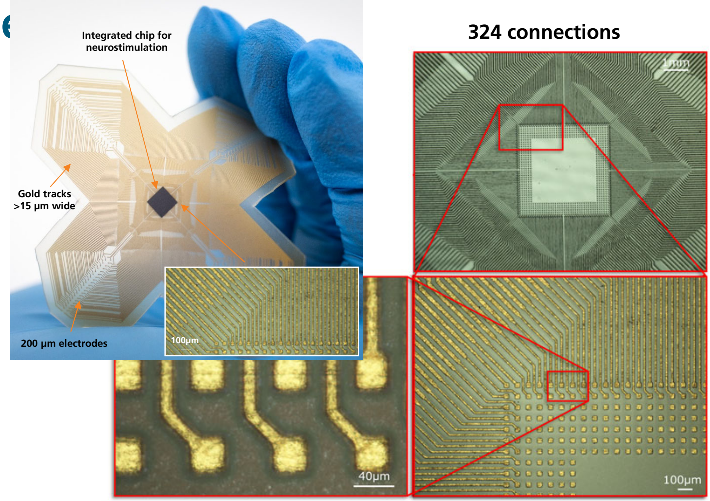
Non-optimized lamination parameters

Optimized lamination parameters

After 100 days soak at 37 °C in PBS

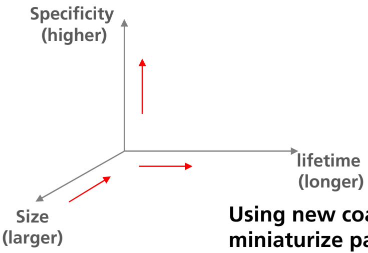
After 6 months in vivo implantation

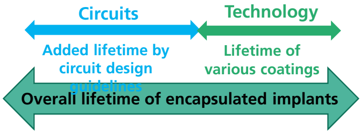
Towards high-density soft active wireless neuroele



Summary

Tailored-designed conformally-coated active neural interfaces can be smaller and with longer lifetimes





Using new coatings and CMOS design to miniaturize packaging

- Contact: Prof. Dr. Vasiliki Giagka, vasiliki.giagka@izm.fraunhofer.de

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Kontakt

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