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Innovation Services
MEMS devices & micro-assembly

Graphene for MEMS devices

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Philips Innovation Services - MEMS foundry

March 29, 2017

Philips MEMS foundry & micro-assembly

- **State-of-the-art cleanroom 2650 m²**
- **Flexibility in materials and substrates**
- High-end micro-assembly factory
- Development + manufacturing
- Certified ISO 9001, ISO 13485

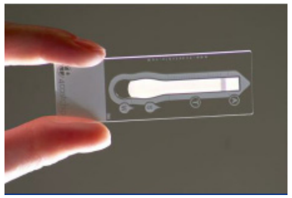
Flow sensor

Air pressure sensor

Micro pump

MEMS mirror

IR sensor for ear thermometer



Micro fluidic chips

Foundry facts

- 2650 m² state-of-the-art cleanroom, class 100 – 1.000
- 150 mm and 200 mm compatible, industrial toolset
- Flexibility to work with many materials ranging from Ag to Zn, including alloys, dielectrics and polymers
- Flexibility to work with substrates: Si, III/V, glass & quartz, square and round
- Unique capabilities to realize 3D structures
- Location: Eindhoven, High Tech Campus

More information:
innovationservices.philips.com/mems-foundry

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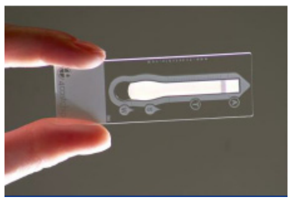

Micro fluidic chips

Foundry facts

ASML
sol voltaics
Holst Centre
NXP founded by Philips
imec
FEI
DALSA
océ
BIOCARTIS
micronit MICROFLUIDICS
miortech
TNO innovation for life

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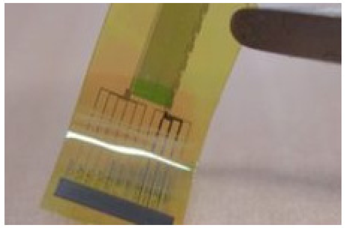
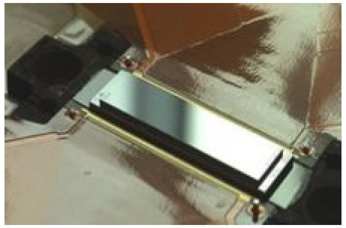
Product portfolio

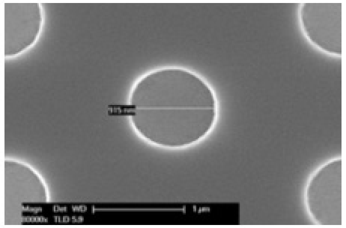
GaN-on-Si



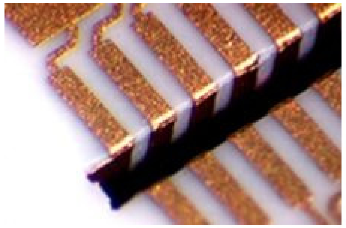
MEMS sensors



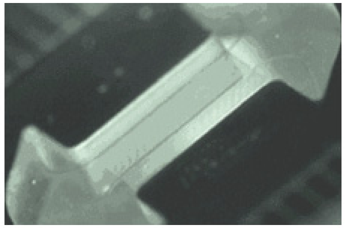
MEMS actuators



Micro sieves



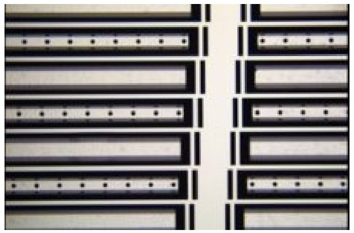
RF passives and interconnect technology



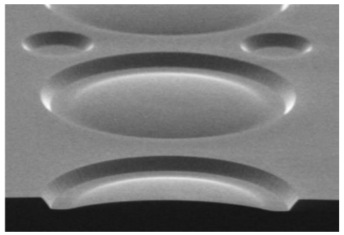
Organ-on-a-chip

Microfluidics

Medical MEMS



Inkjet printheads



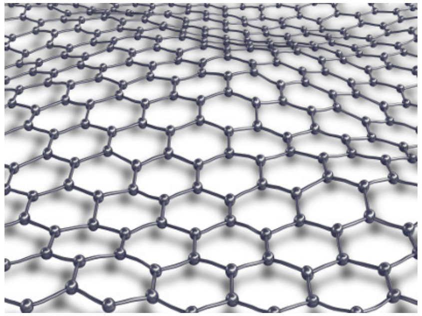
Optical elements

Membranes

More information:
innovationservices.philips.com/mems-foundry

Why is graphene interesting?

• Thinnest material around:	1 atom
• Strong material:	Y ≈ 1 TPa; UTS = 130 GPa
• Very stretchable:	up to 20%
• Almost completely transparent:	97.7%
• Largest surface to weight ratio:	2,700 m^2/g
• Very high thermal conductivity:	5000 W/m K
• Extreme electrical conductivity:	200,000 cm^2/Vs



Combine existing fab-facilities with a new unique material

Focus on "unique to graphene applications"

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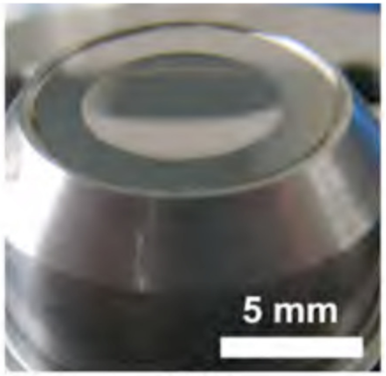
Unique to graphene: X-ray windows

Current industry standard material is Beryllium. Multilayer graphene shows increased performance not achievable with other materials.

	Beryllium*	Graphitic carbon*
No support grid at 7mm opening diameter	Yes	Yes
Thickness	8 um	**1 um**
X-ray transmission at 1.5 keV	71%	**85%**
Pressure stability (> 2 bar)	Yes	Yes
Pressure cycle fatigue	> 20 k	**> 500 k**
Helium leak rate (mbar L/s)	$< 10^{-10}$	$< 10^{-10}$
Light tight	Yes	Yes
Chemical resistance	High	High
Non-toxic	No	**Yes**
Availability/Supply	Limited	**Unlimited**



** S. Huebner et al., IEEE Transactions on Nuclear Science 99, 2015*

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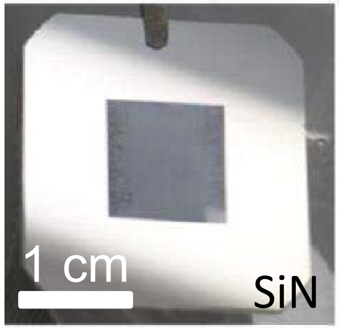
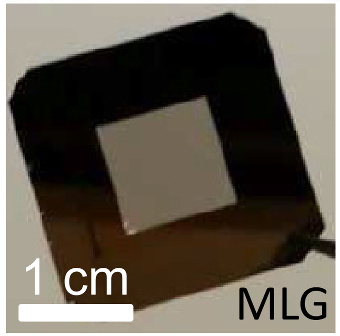
Unique to graphene: EUV windows

Current industry standard for EUV pellicles to protect reticles from particle contamination are pSi based membranes. (Multilayer-)graphene outperforms current standard where every % gain has huge impact.

	pSi [1)]	SiN [1)]	MLG [1)]
Thickness (nm)	50	13	6
Single pass EUV transmission (%)	< 86	90	**> 95**
Emissivity	< 0.01	0.001	**0.4**
Capping layer needed	Yes	Yes	**No**
Stable at high temperatures	< 800 °C		**> 1000 °C**
EUV/H2 compatible	Yes	Yes	Yes
UTS (Gpa)	7	10	**130***
Demonstrated size (cm)	11 x 14	11 x 14	5 x 5 [2)]

*single layer graphene value





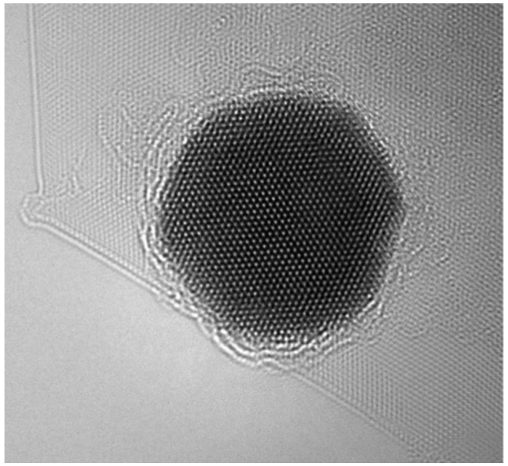
1) M. Peter et al., euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016
2) S-G Kim et al., Nanoscale 7, 14608, 2015

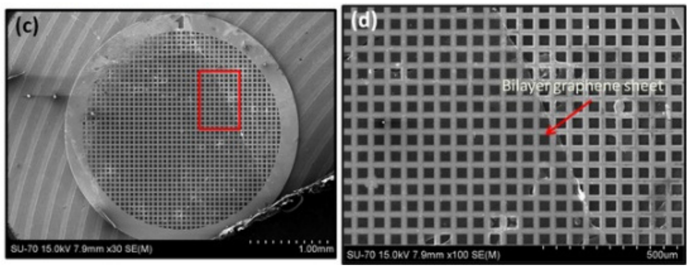
Unique to graphene: TEM grids

Graphene can be used as ultra low contrast TEM substrate for high-end TEM imaging.

	SiN	MLG [1,2]
Thickness (nm)	> 5	**> 0.34**
Conductive (no charging)	No	**Yes**
Emissivity	0.001	0.4
Inert	Yes	Yes
Stable at high temperatures	< 1000 °C	> 1000 °C
UTS (Gpa)	10	**130***
Atomic mass	28–14	**12**
Nano particle size suitability	≳ 10 nm	**≳ 1 nm**

*single layer graphene value





1) *R. Hawaldar et al., Scientific Reports* **2**, 682 (2012)
2) Z. Lee et al., Nano Lett 9, 3365 (2009)

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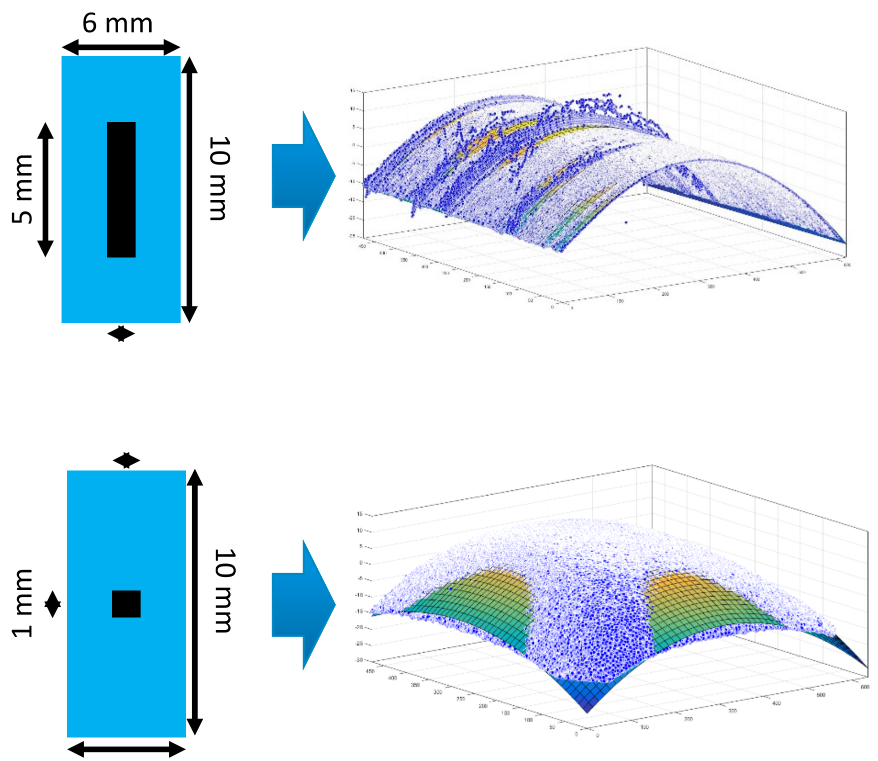
Is large area graphene still exceptionally strong?

Use simple transfer to investigate graphene material properties at large scale.
Bulging membranes to determine Youngs Modulus and Poisson ratio.



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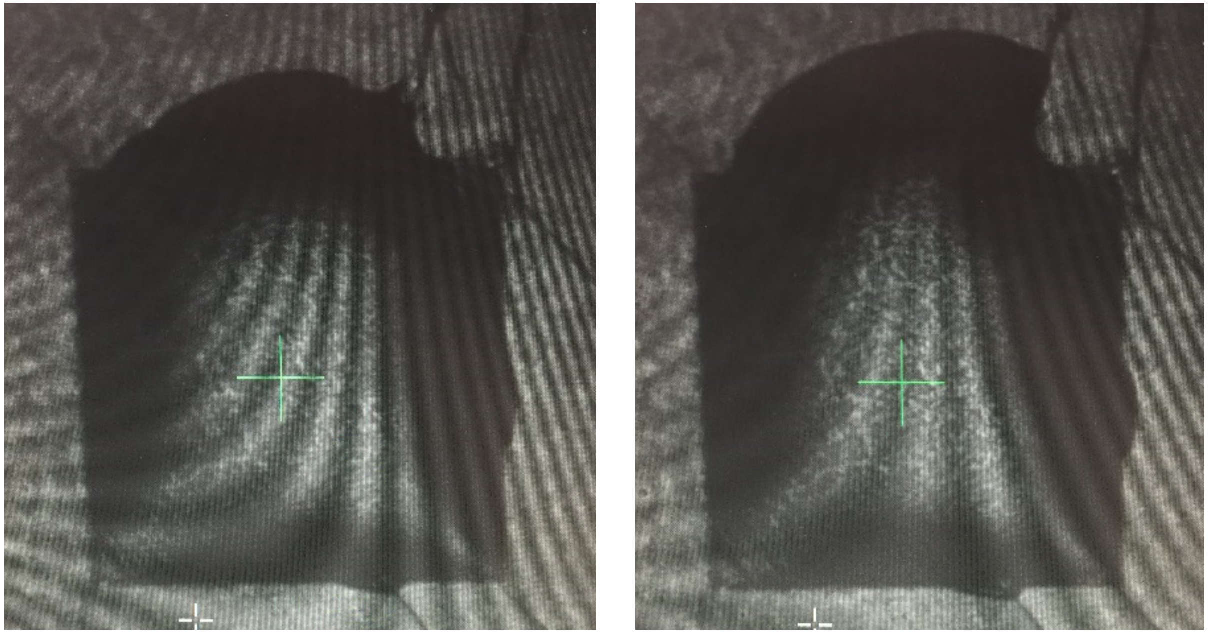
Transferred graphene is blown off

Illustration of bulging a manually transferred membrane



Delamination of MLG from the substrate.
Worse for thicker layers.
Need to improve adhesion or find different fabrication routes.

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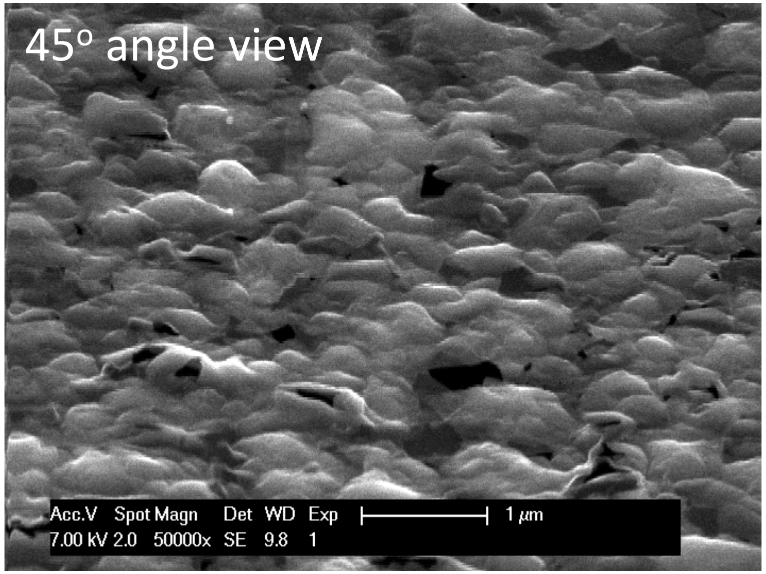
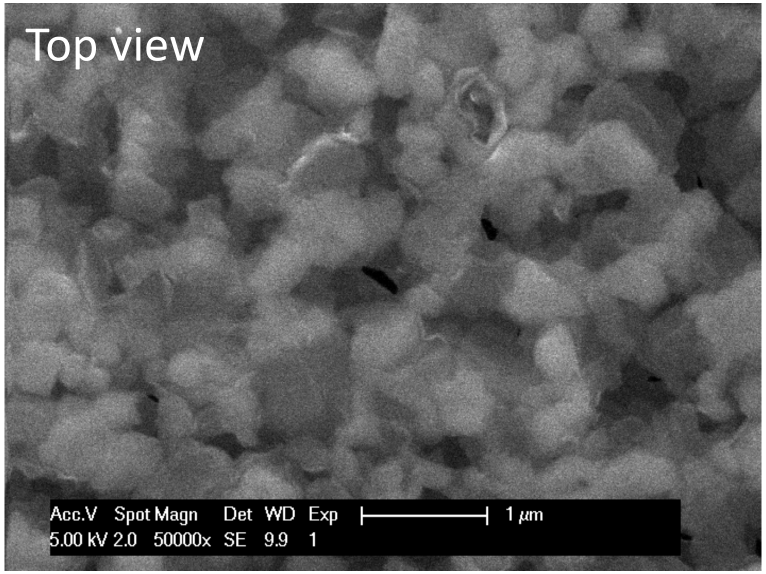
Quality of multilayer graphene membranes

SEM images of the 53 nm thick multilayer graphene (graphite) membrane is shown below (Similar results for thinner membranes).

- Thickness variations of the graphene grains (roughly 500–1000 nm in size).
- Holes (black spots) in the graphene layer.
- Roughness of the substrate imprinted in the multilayer graphene membrane





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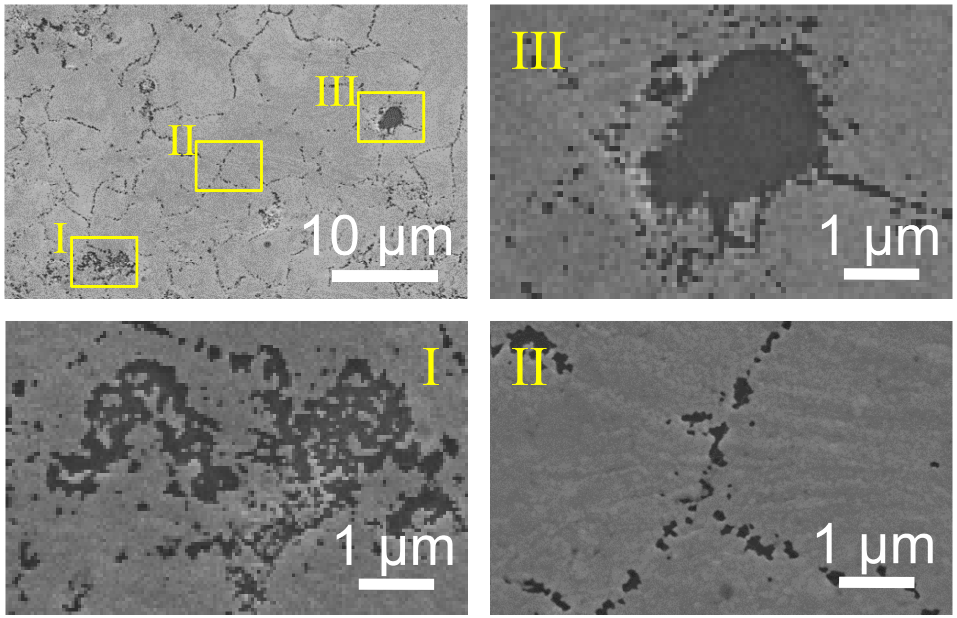
Quality of commercially available graphene

Single layer

- Commercially available material far from ideal mono-layer:
  - Patchwork of perfect crystals (many grain boundaries)
  - Atomic defects visualized by metal etch test
- Further optimization needed; move to multilayers if application allows

SEM images of etched metal underneath graphene



AJM Giesbers et al. Solid State Communications 229 (2016) 49–52

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Why not to go for transfer in our applications?

Manual transfer of a multilayer graphene sheet over an open frame.

Advantages	Disadvantages
Quick (fast testing of material)	Unknown adhesion
Minimum of processing (low risk to damage graphene or additional contaminants)	Reproducibility (quality is not constant)
Cheap quick test	Folds and wrinkles
	Not suitable for volume production
	Time consuming fabrication

For our way of working this means transfer is a no go
→ **need integrated process in order to go for volume production.**

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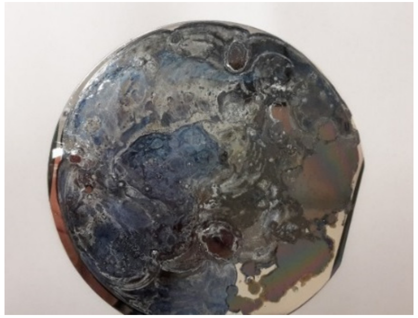
Challenges and solutions in integration

- Key challenges to get to integrated process flows
  - High quality graphene on wafer scale
  - High temperature graphene growth incompatible with standard processing
  - Removal of metal catalyst (without transfer)

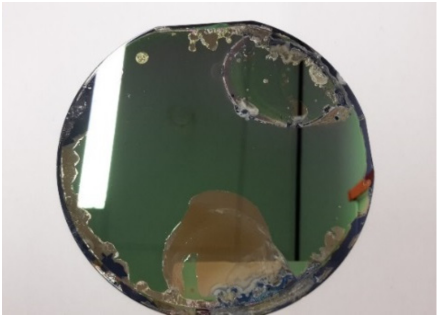
- Graphene integration in process flows leads to practical issues
  - Adhesion/delamination of graphene or subsequent layers, nucleation of subsequent layers, interfering catalyst layer, resist residues, O2-plasma etching of graphene, …

We solved many of these issues for specific applications and added materials

Metal catalyst not resistant to standard wafer cleaning



Poor adhesion of dielectrics during processing



Poor adhesion of metal contacts to graphene.

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Way forward

- **Industrialization challenges**
  - Processing / integration in a manufacturing process.
  - Large scale availability and availability at large scale.
  - Quality of the material (uniformity, lifetime, repeatable); Control over properties.

- **MEMS foundry current activities**
  - Partnerships with academia and industry
  - Evaluation of various graphene sources and application concepts
  - Integration of graphene in process flows for selected applications

- **Expectations from industry / startups / academia**
  - New customer projects with graphene unique applications.

- **Philips view on most promising business opportunities, and their time to market**

– Membranes	2-3 yr
– MEMS	3-5 yr
– Photo detection	5-7 yr
– Plasmonics	5-10 yr

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Conclusions

- Graphene
  - In theory and lab the perfect material with many interesting properties
  - Can it hold its promise in applications
  - Good potential for MEMS devices

- Challenges
  - Availability of high-quality, large area material
  - Integration in process flows
  - Unique to graphene applications

- Philips Innovation Services MEMS foundry
  - Developing integrated process flows for multiple applications
  - Active in ecosystem
  - Open for new projects

Acknowledgements

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How can we help to **accelerate your innovation?**

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