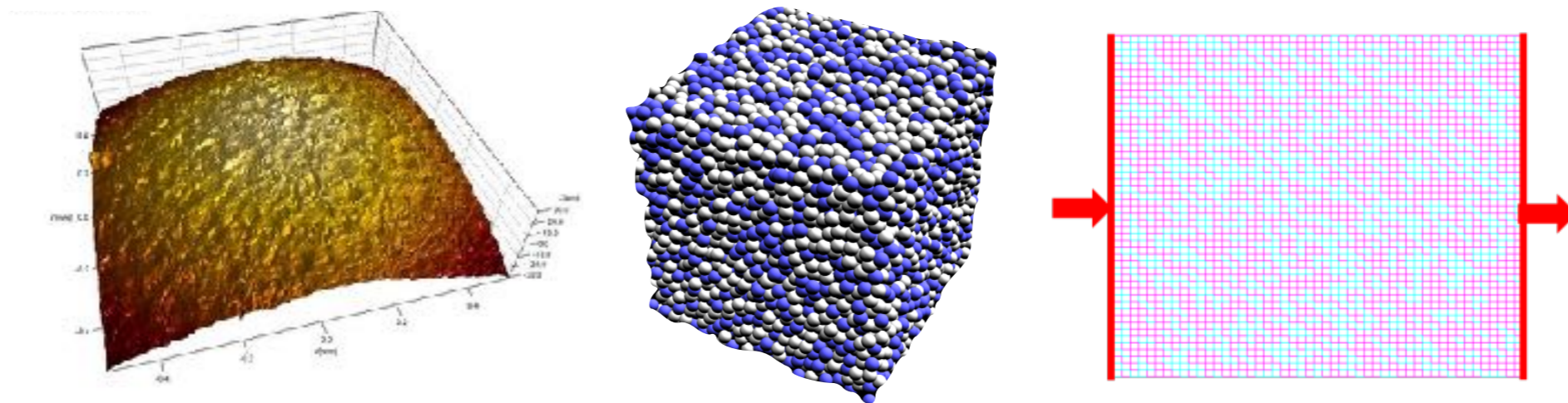


Electrical Conduction in Compacted Granular Materials:

From Contact Mechanics to Complex Networks



Yixiang Gan

School of Civil Engineering

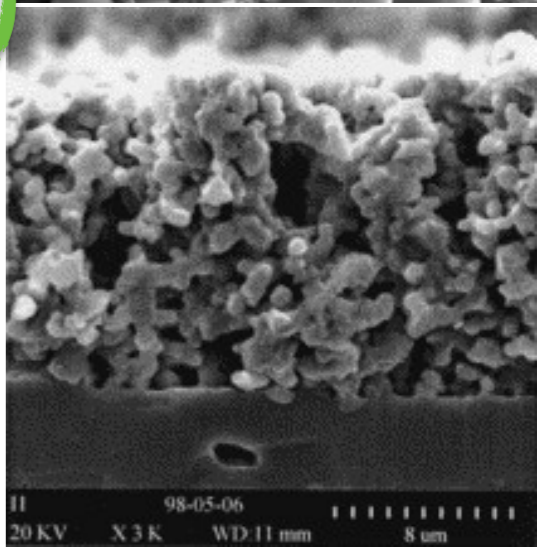
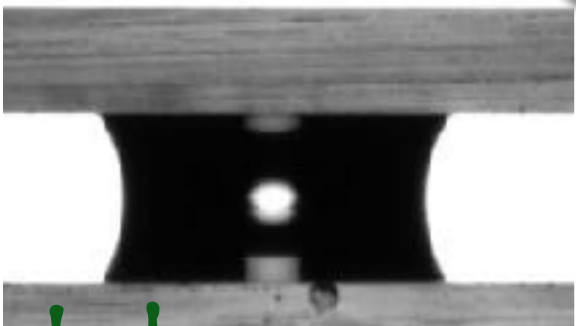
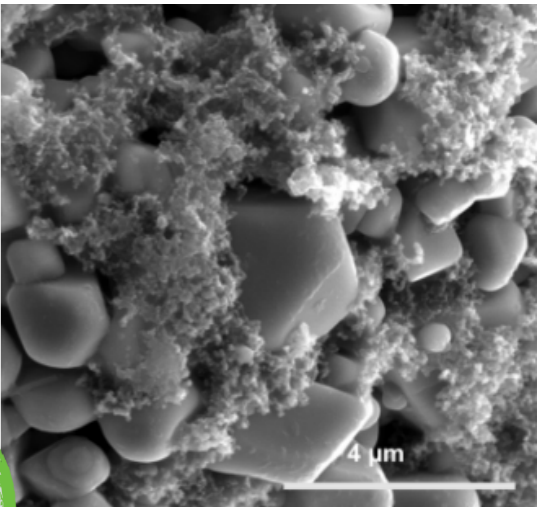
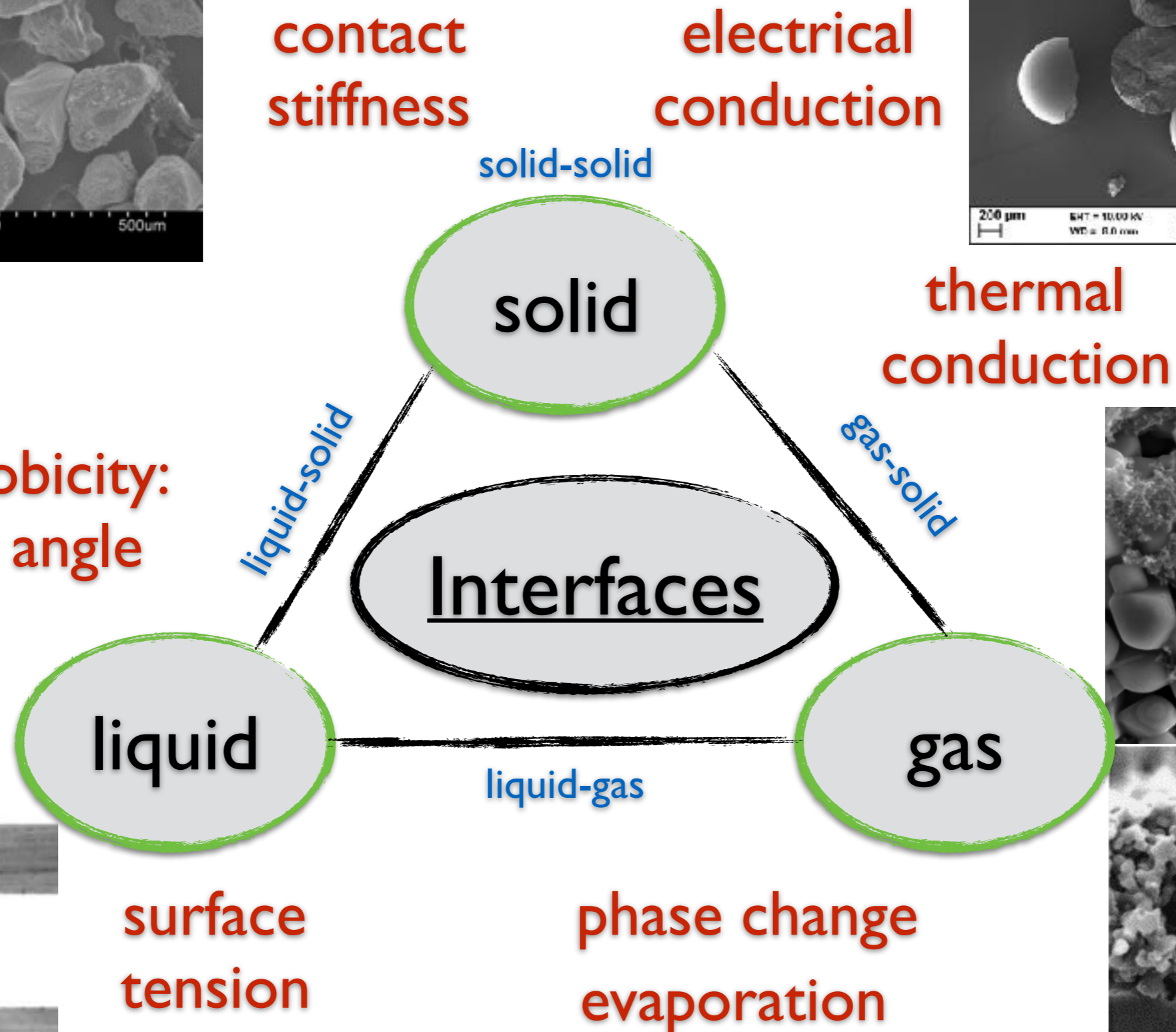
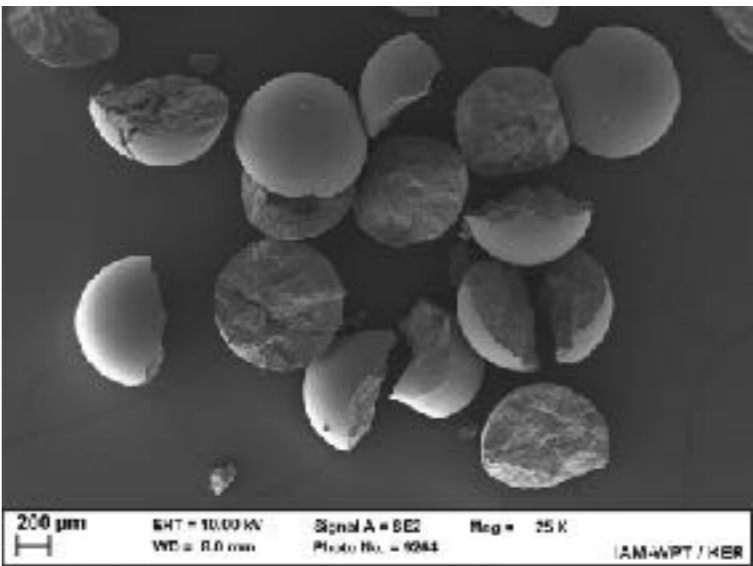
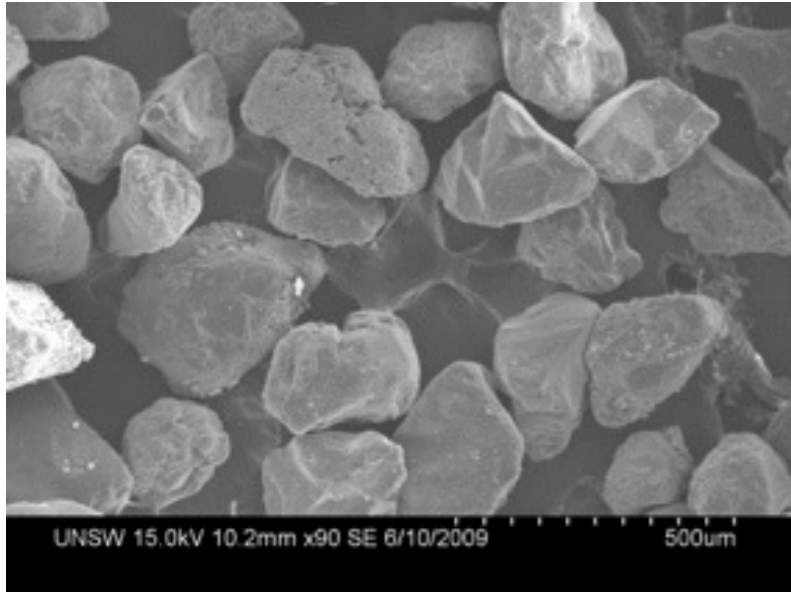
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2018 STLE Annual Meeting, Minneapolis

Granular materials



Outline

- **Background:** effective properties of granular systems
- **Rough surfaces:** contact stiffness and electrical contact resistance
- **Network properties:** stress-dependent RC response and its scaling
- **Conclusion**



Dr Chongpu Zhai
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Dr Julia Ott
(Bosch)



Oleg Birkholz
(KIT)

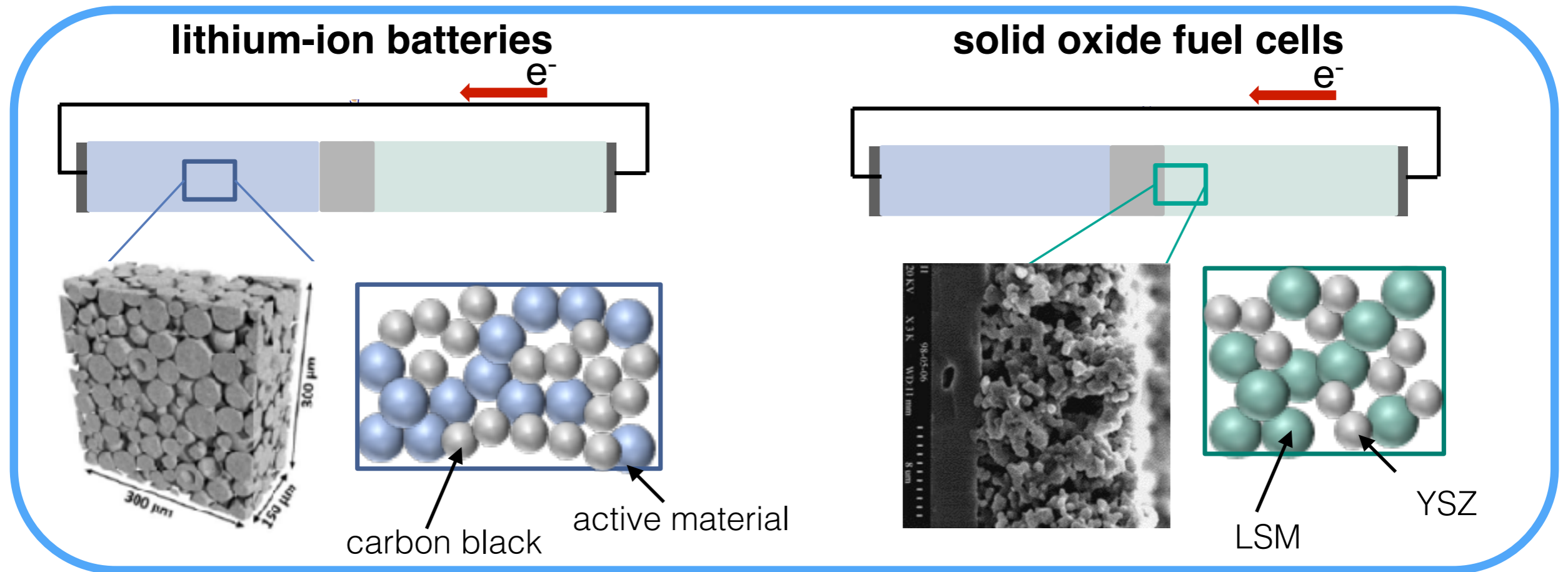


Si Suo
(USYD)



Dr Dorian Hanaor
(TUB)

Background: Granular electrode structures

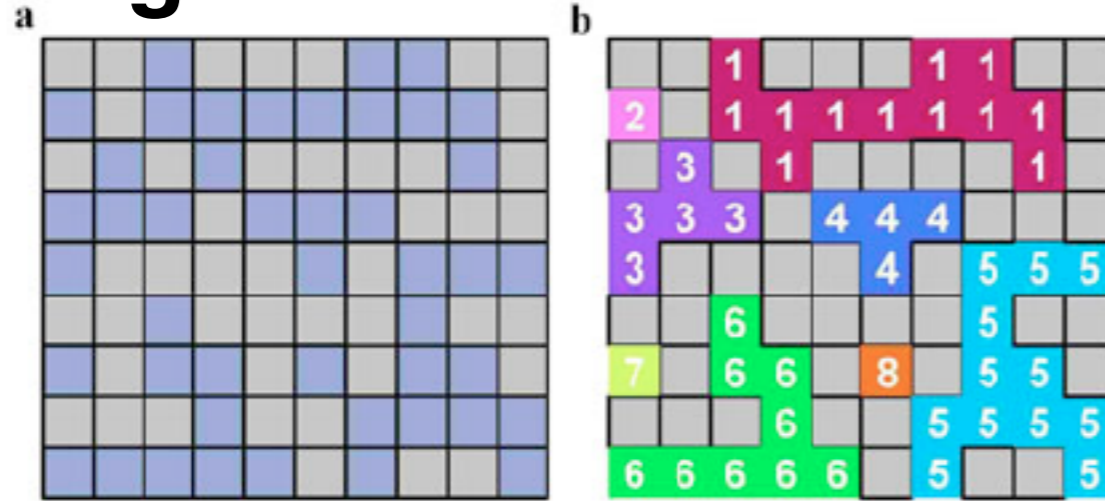


3M

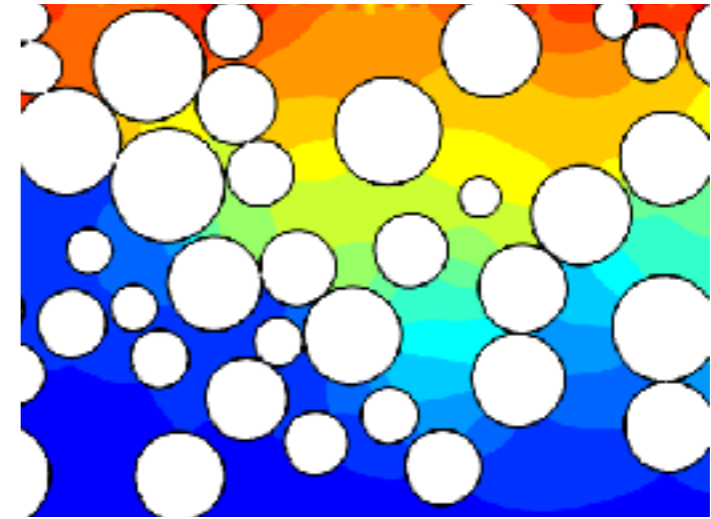
Multi-physics
Multi-phase
Multi-scale

- Both SOFC and LIB have porous electrode structures
- electrode structures approximated as binary mixture of spherical particles
- Similar electrode structures enable to use the same computational methods

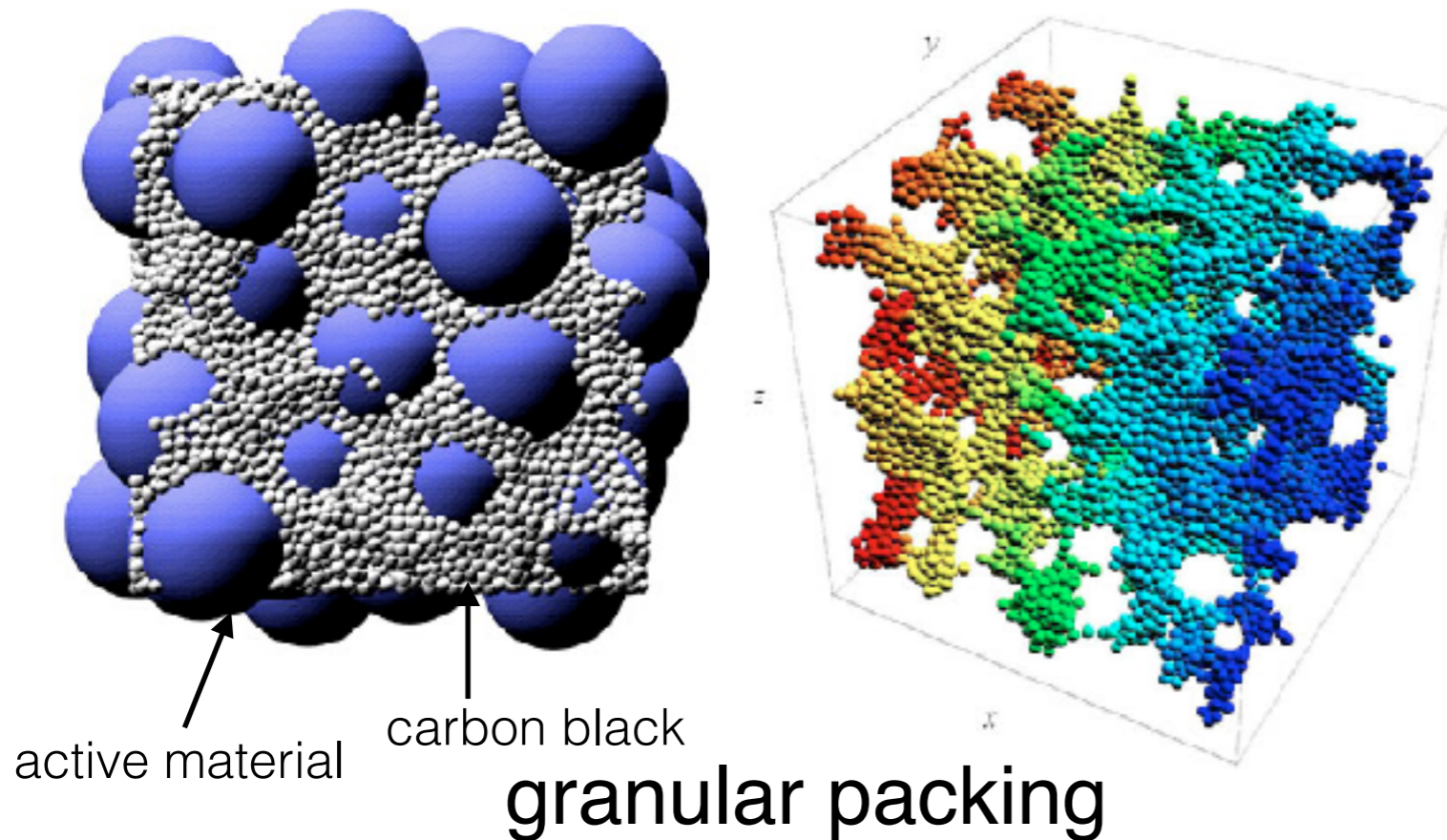
Modelling Li-ion batteries



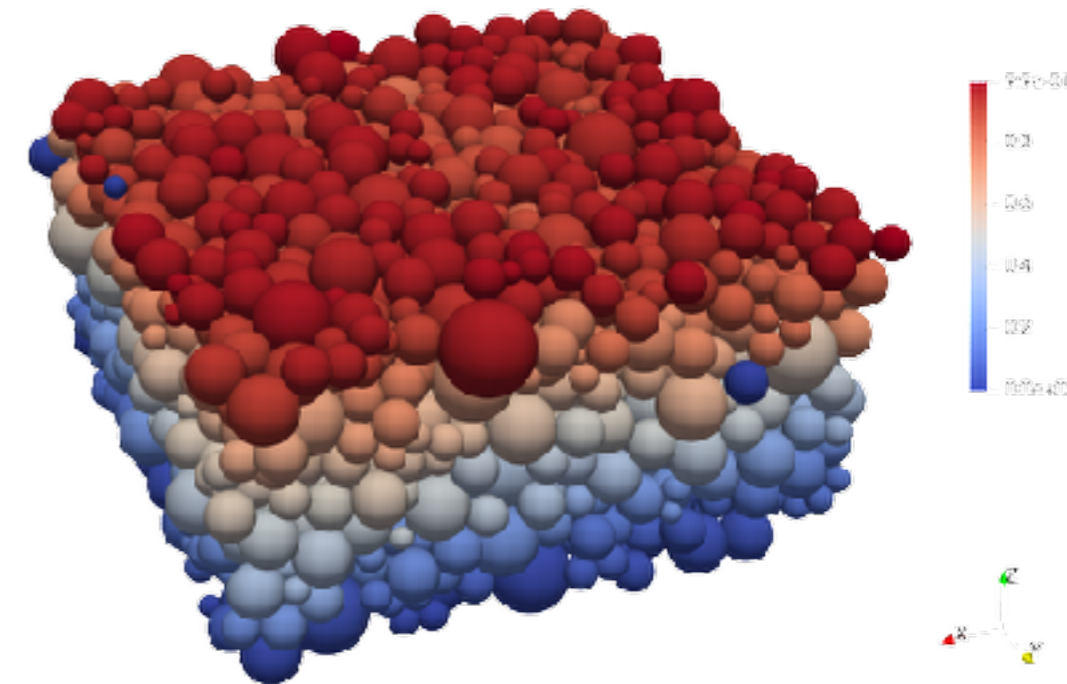
percolation



pore space modelling



granular packing



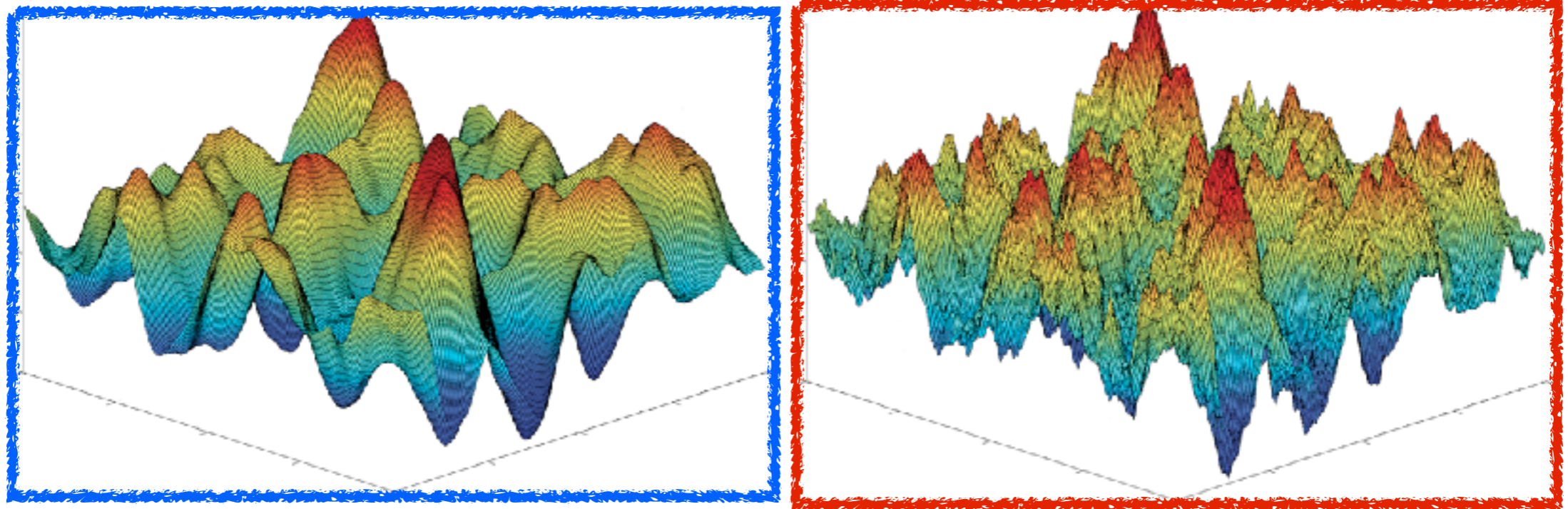
resistor network

interface,
contact mechanics

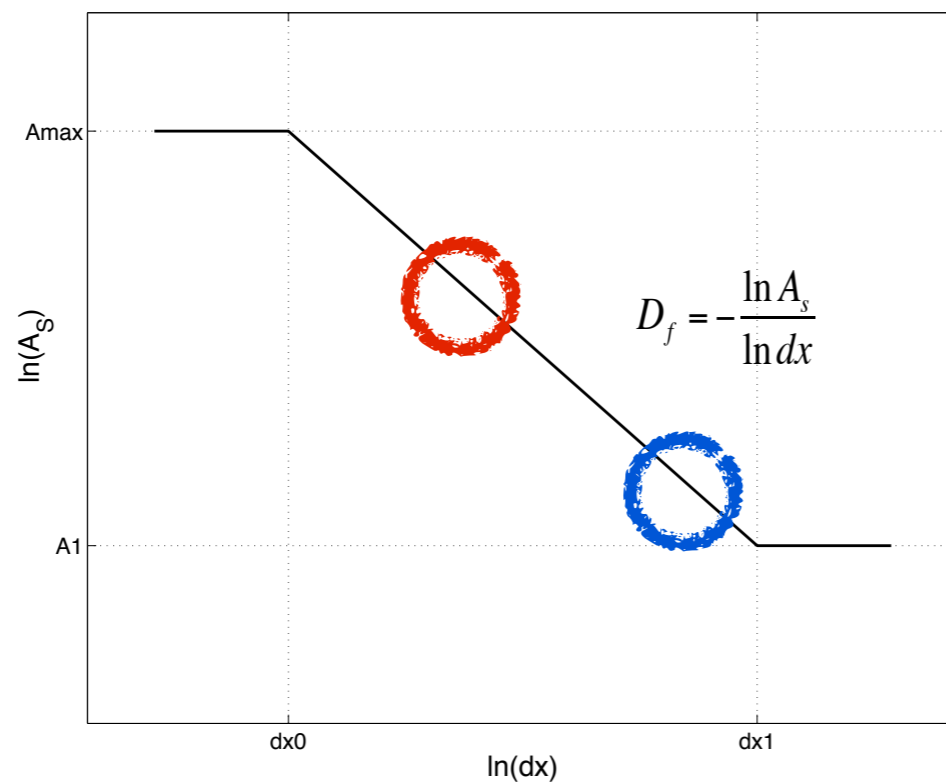


effective properties,
complex network

Surface roughness vs fractality



same mean roughness, different fractality

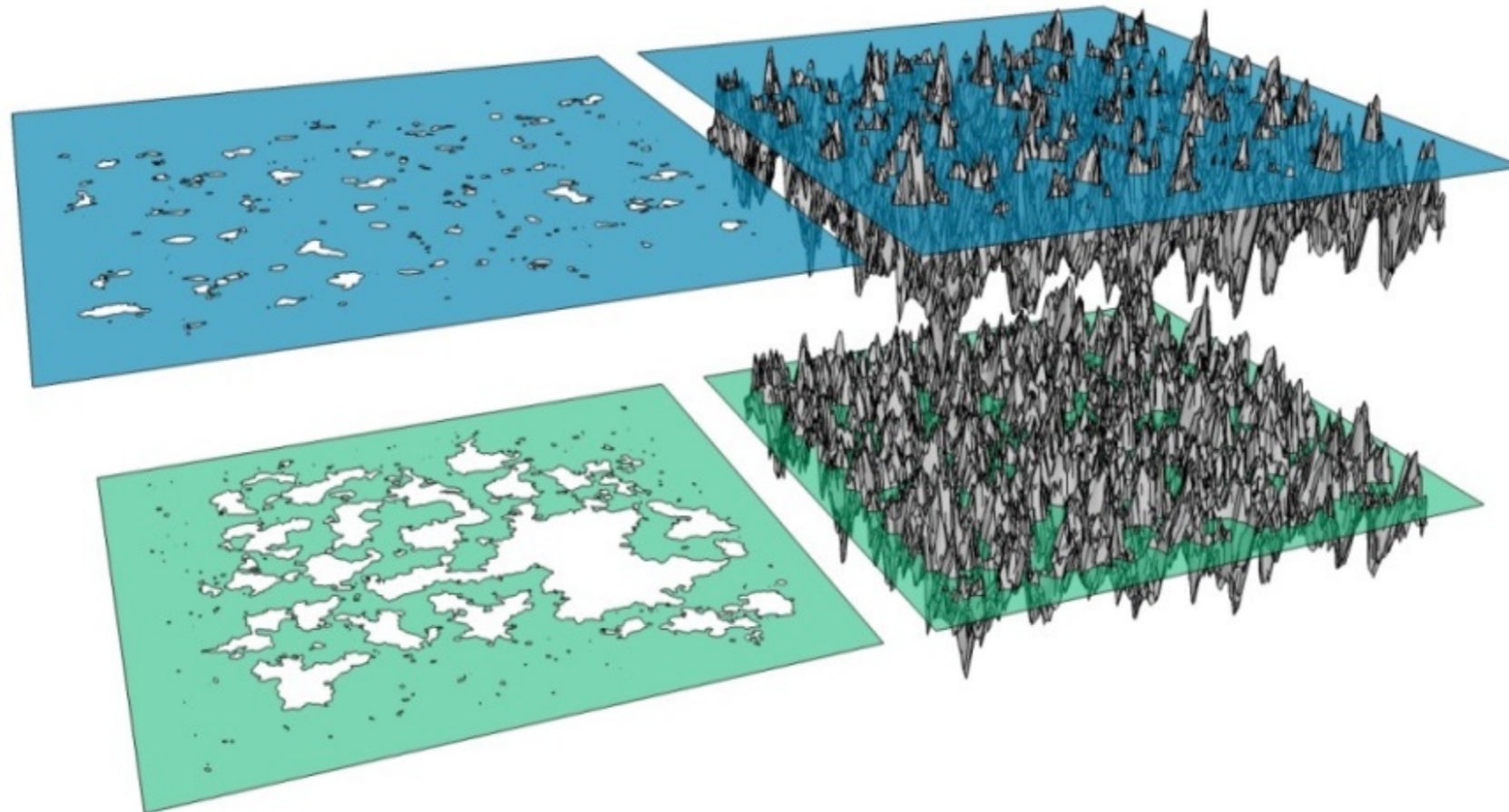
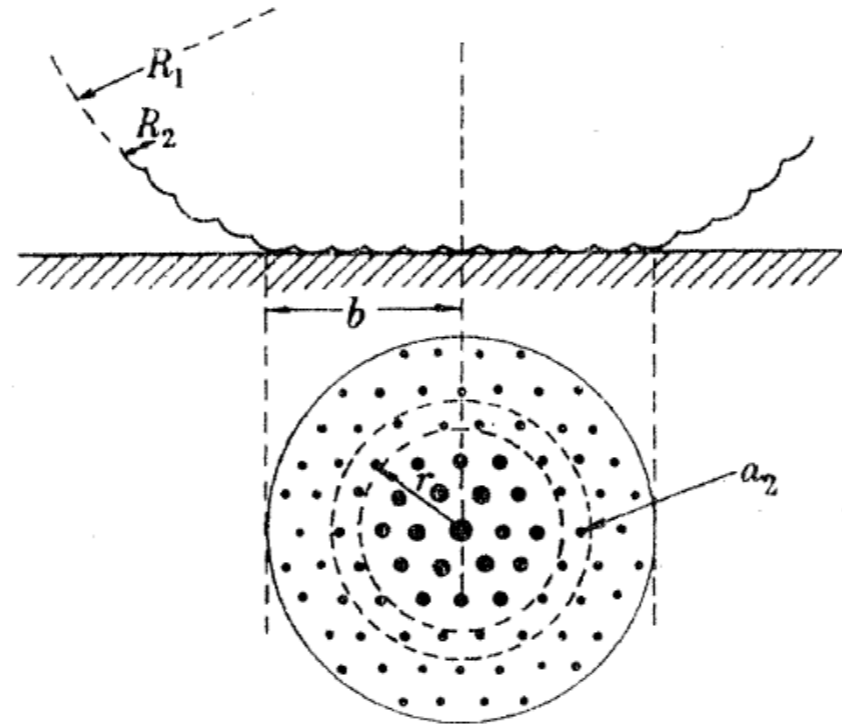


effective surface area

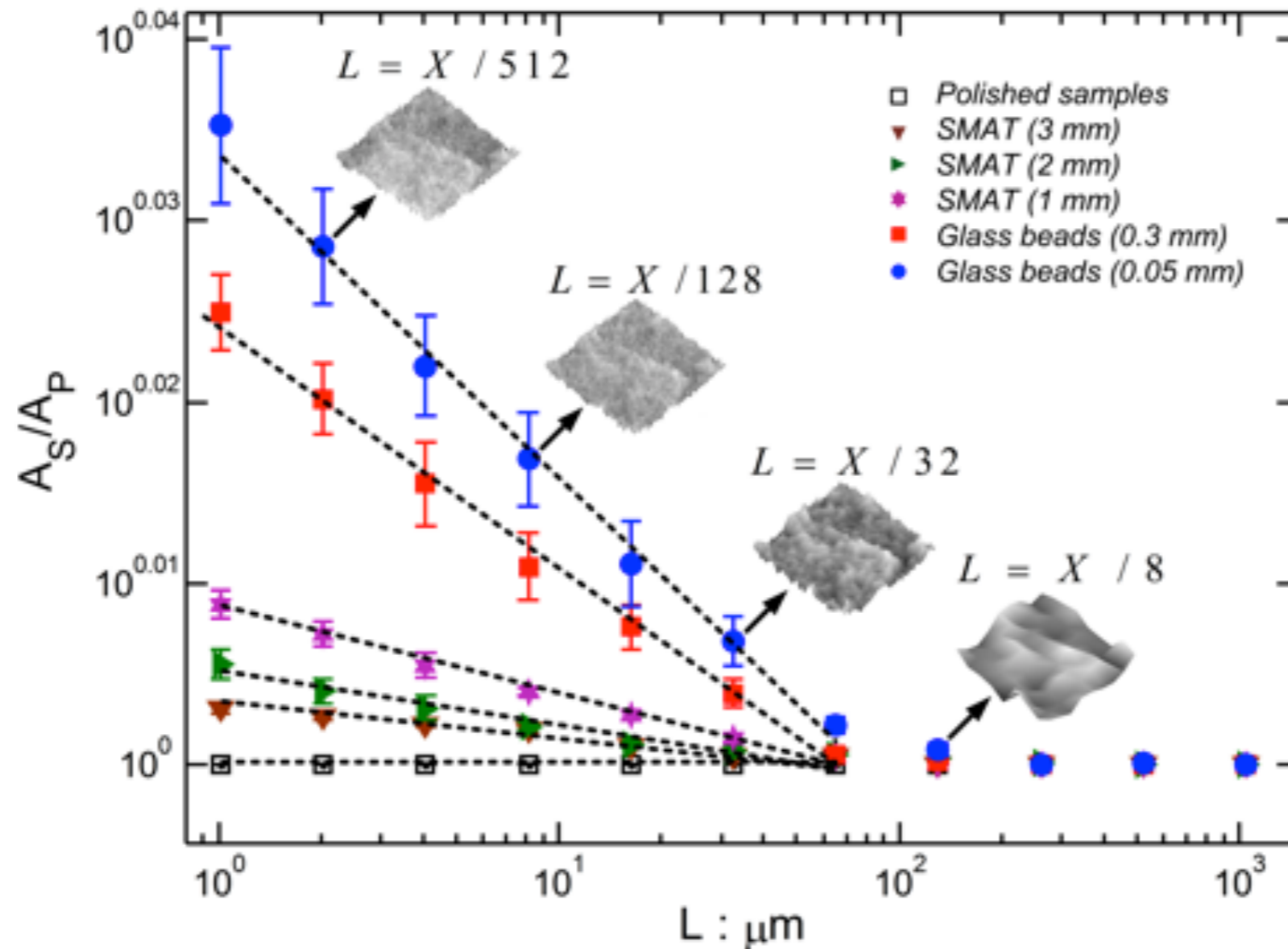
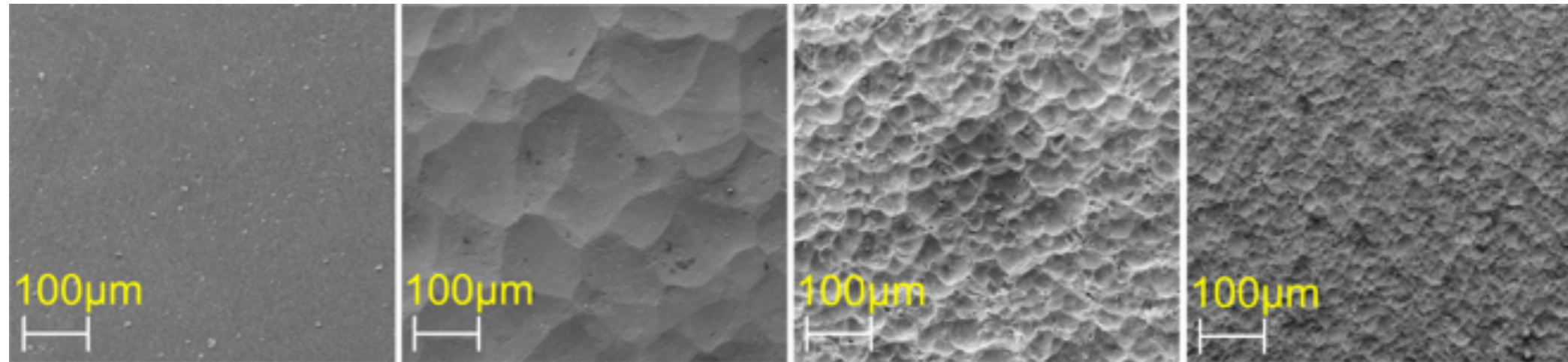


effective contact area

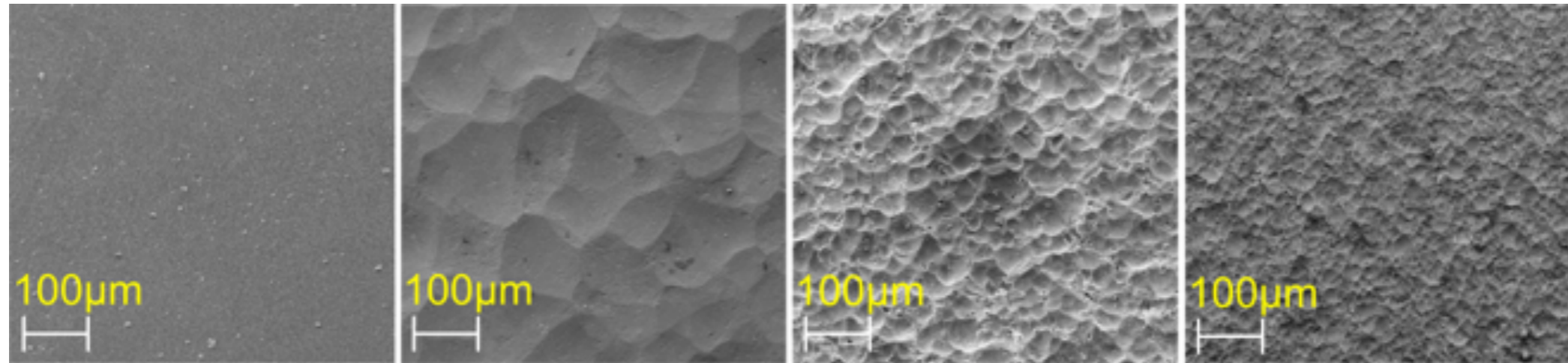
Contact stiffness and electrical contact resistance



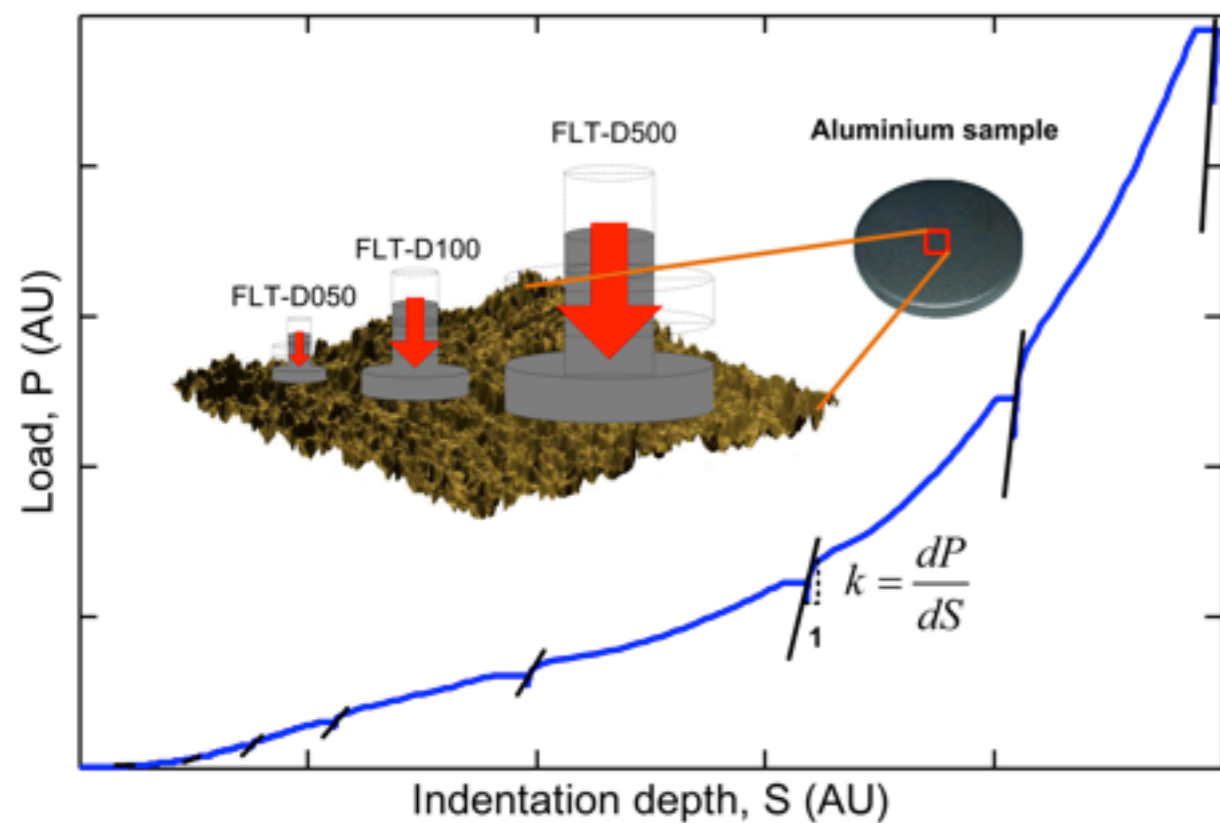
Rough surfaces: fractal dimension



Contact stiffness and electrical resistance measurement

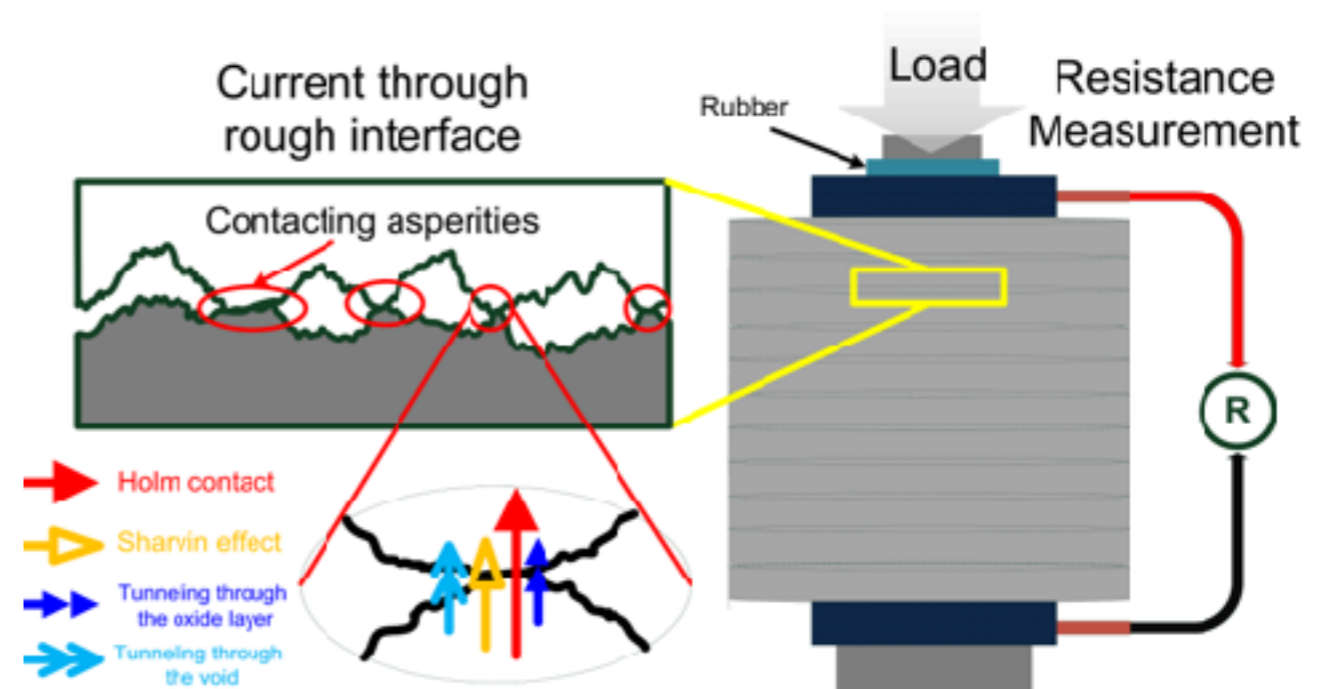


(a) nano-indentation



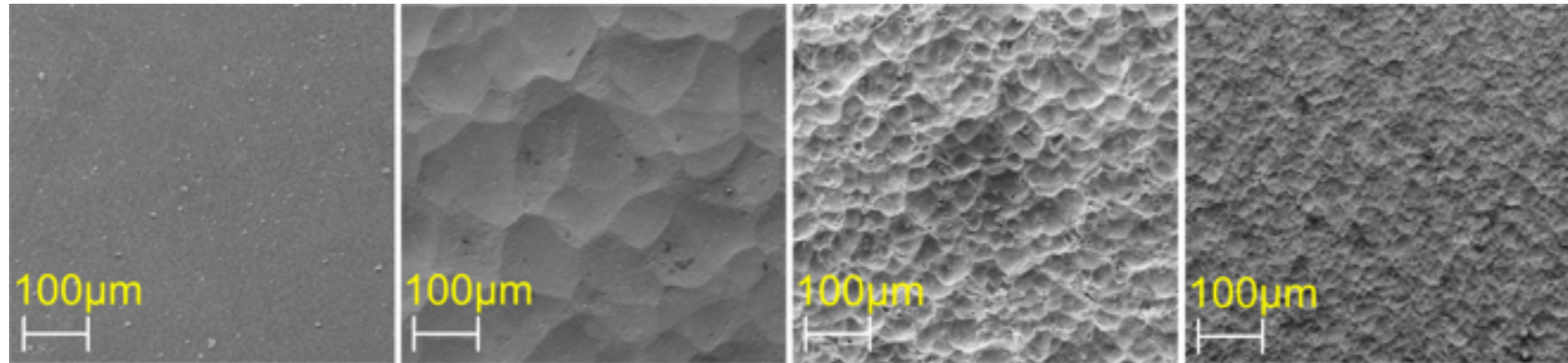
$$E_c = \beta_E (F)^{\alpha_E}$$

(b) ECR measurement

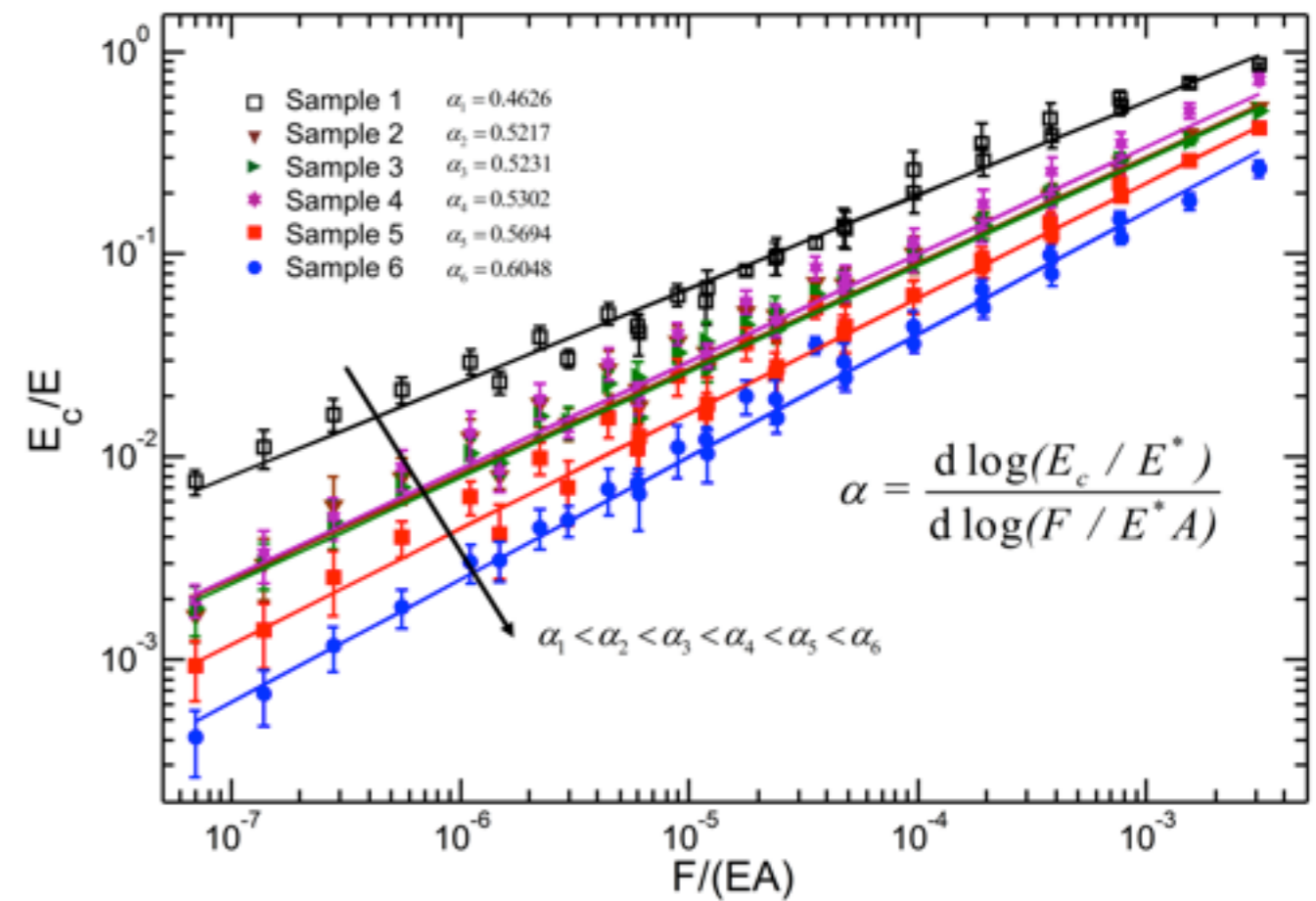
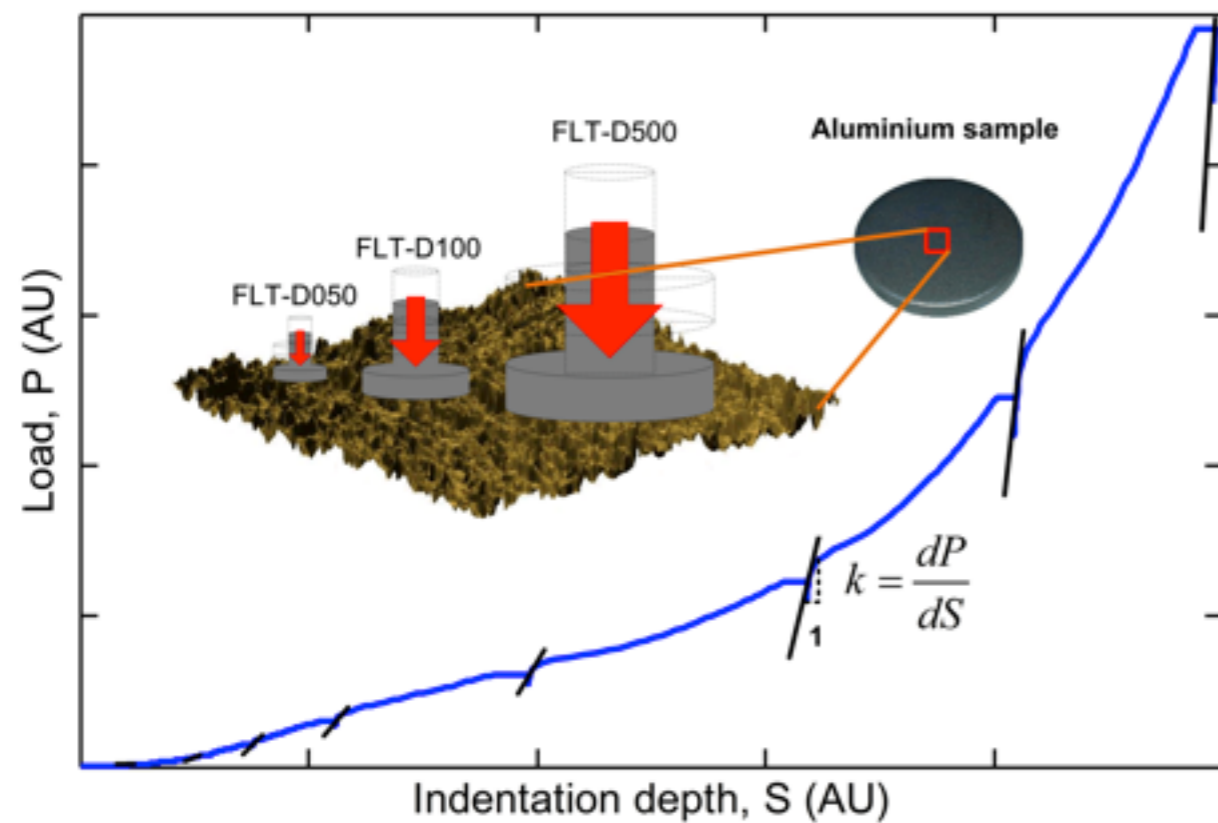


$$G_c = \beta_G (F)^{\alpha_G}$$

Contact stiffness at rough surfaces



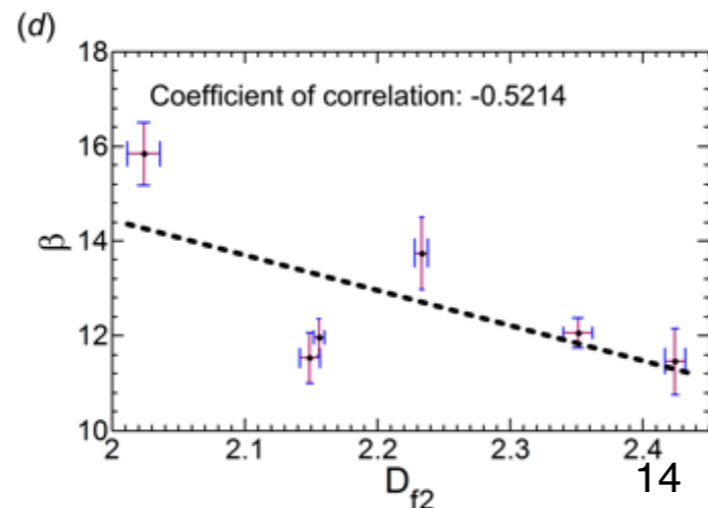
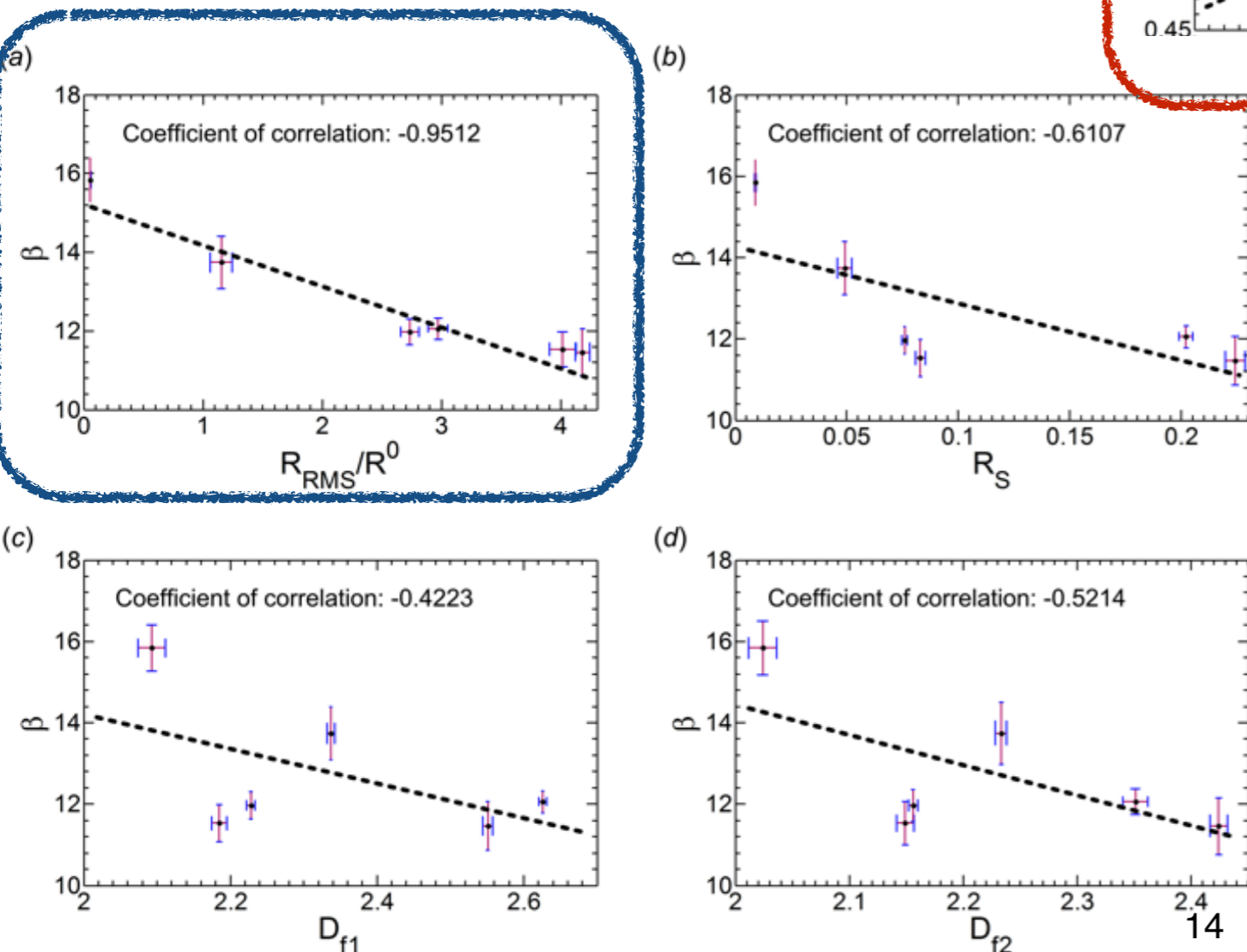
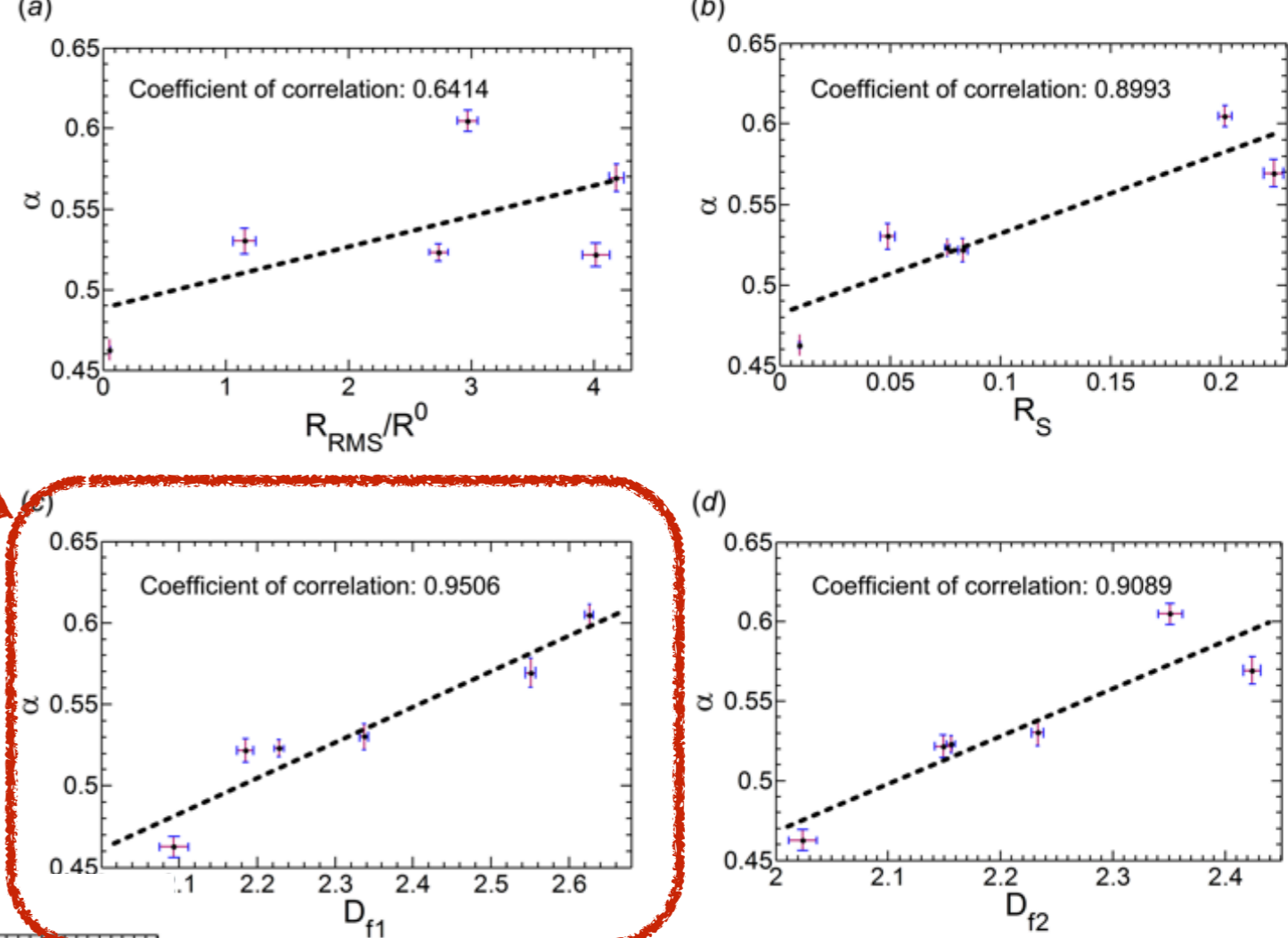
(a) nano-indentation



$$\frac{E_c}{E} = \beta \left(\frac{F}{EA} \right)^\alpha$$

Contact stiffness: correlation analysis

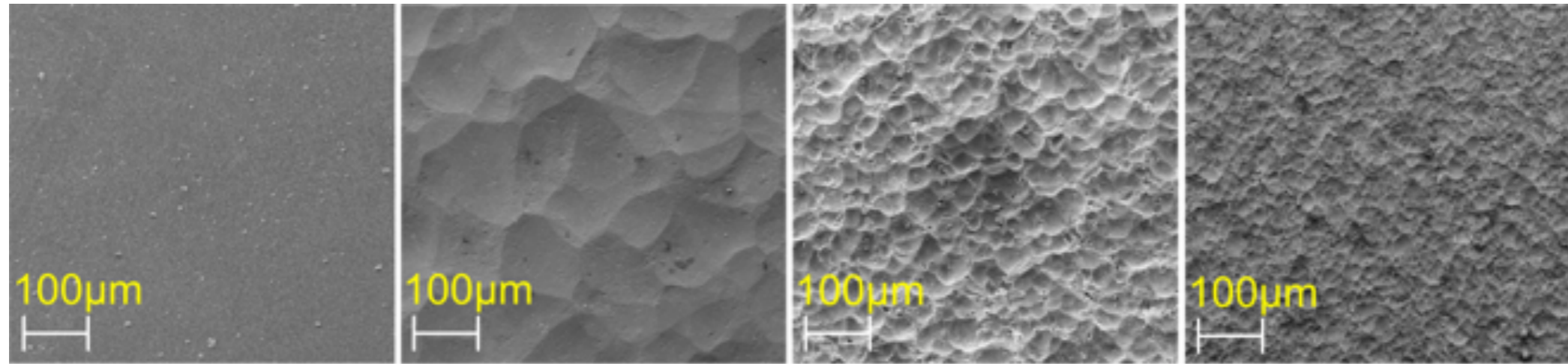
$$\frac{E_c}{E} = \beta \left(\frac{F}{EA} \right)^\alpha$$



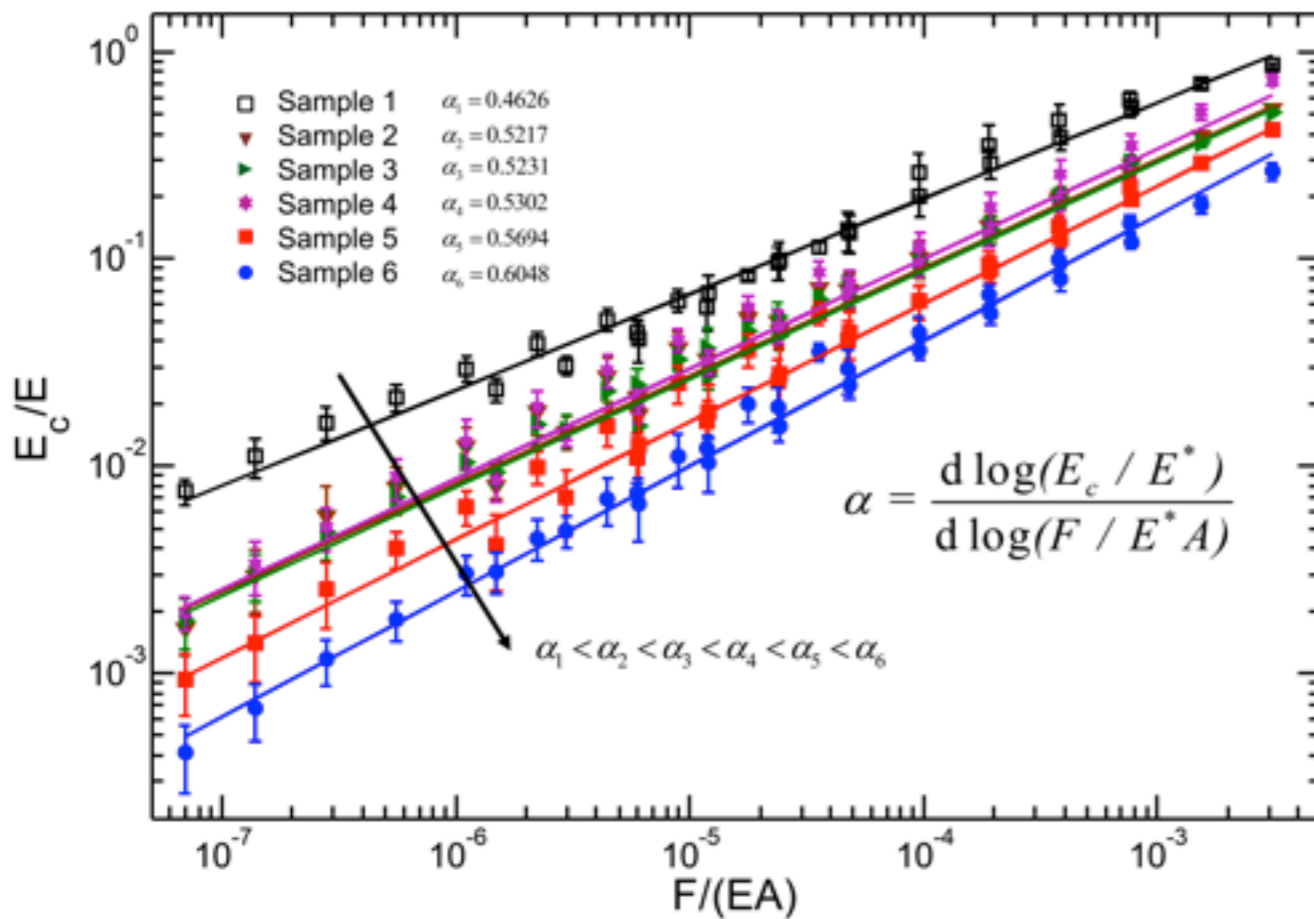
- RMS roughness
- RMS slope
- Fractal dimension

Hertzian contact: $a=1/3$

Contact stiffness and electrical contact resistance

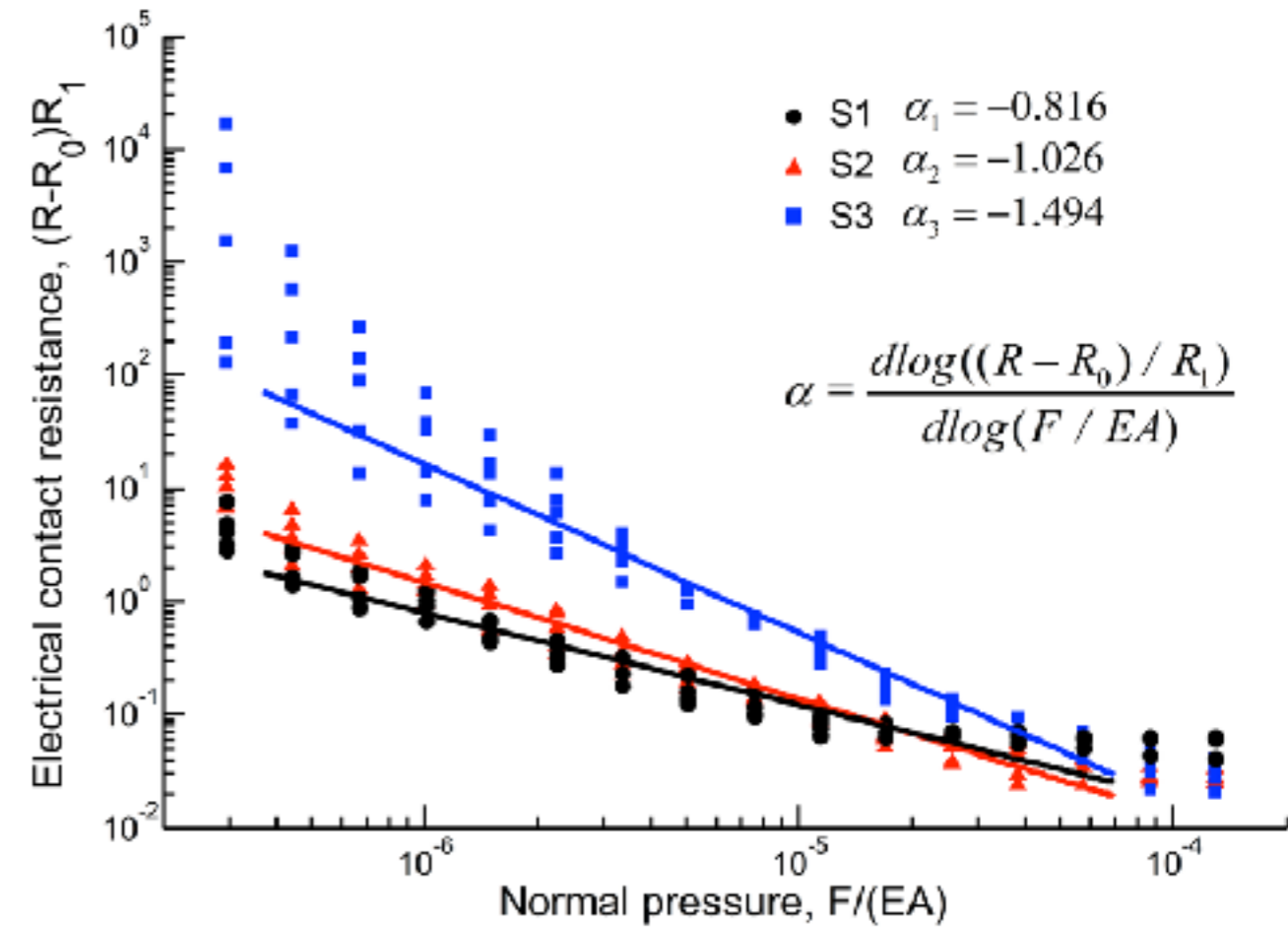


(a) nano-indentation



$$E_c = \beta_E (F)^{\alpha_E}$$

(b) ECR measurement

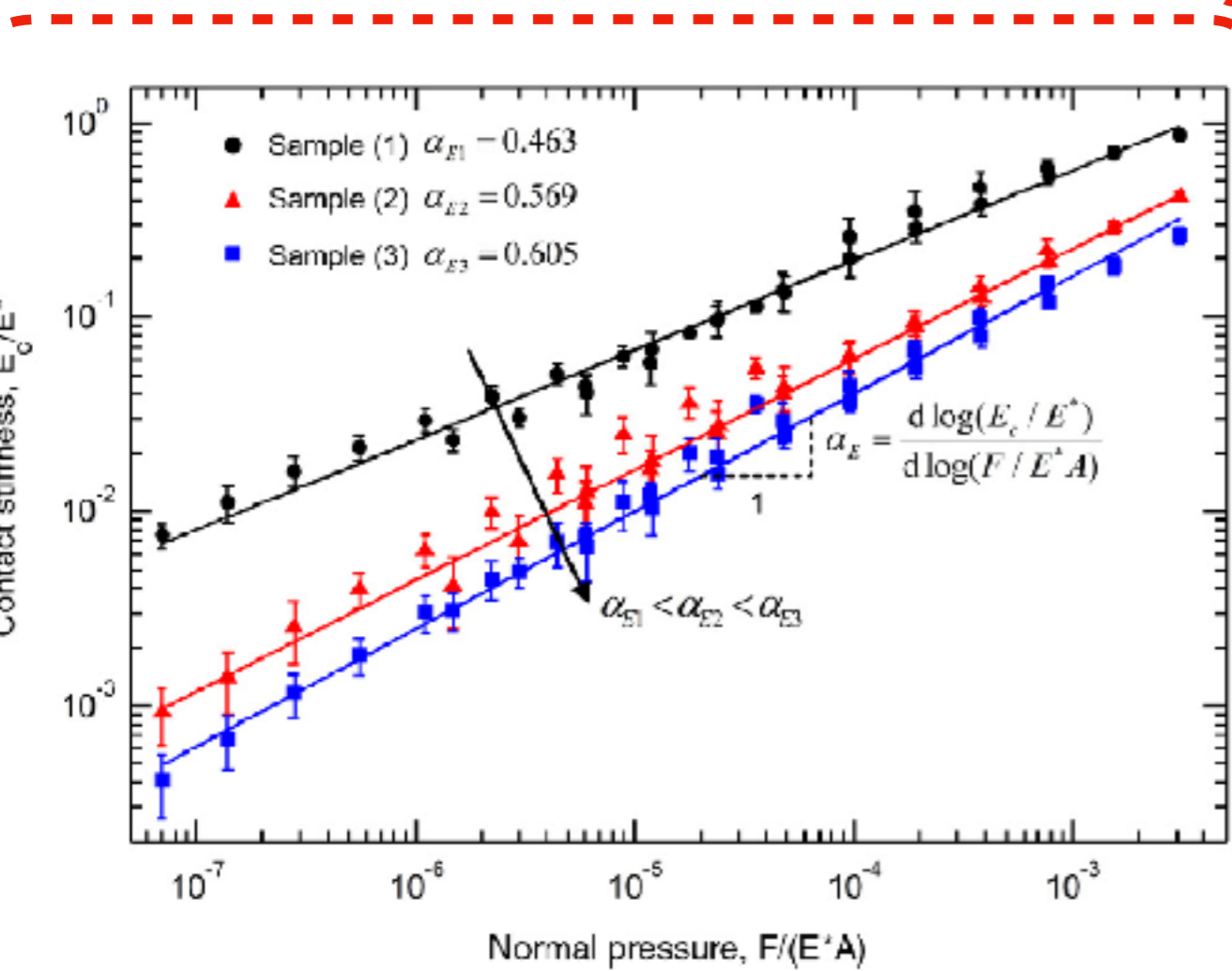


$$G_c = \beta_G (F)^{\alpha_G}$$

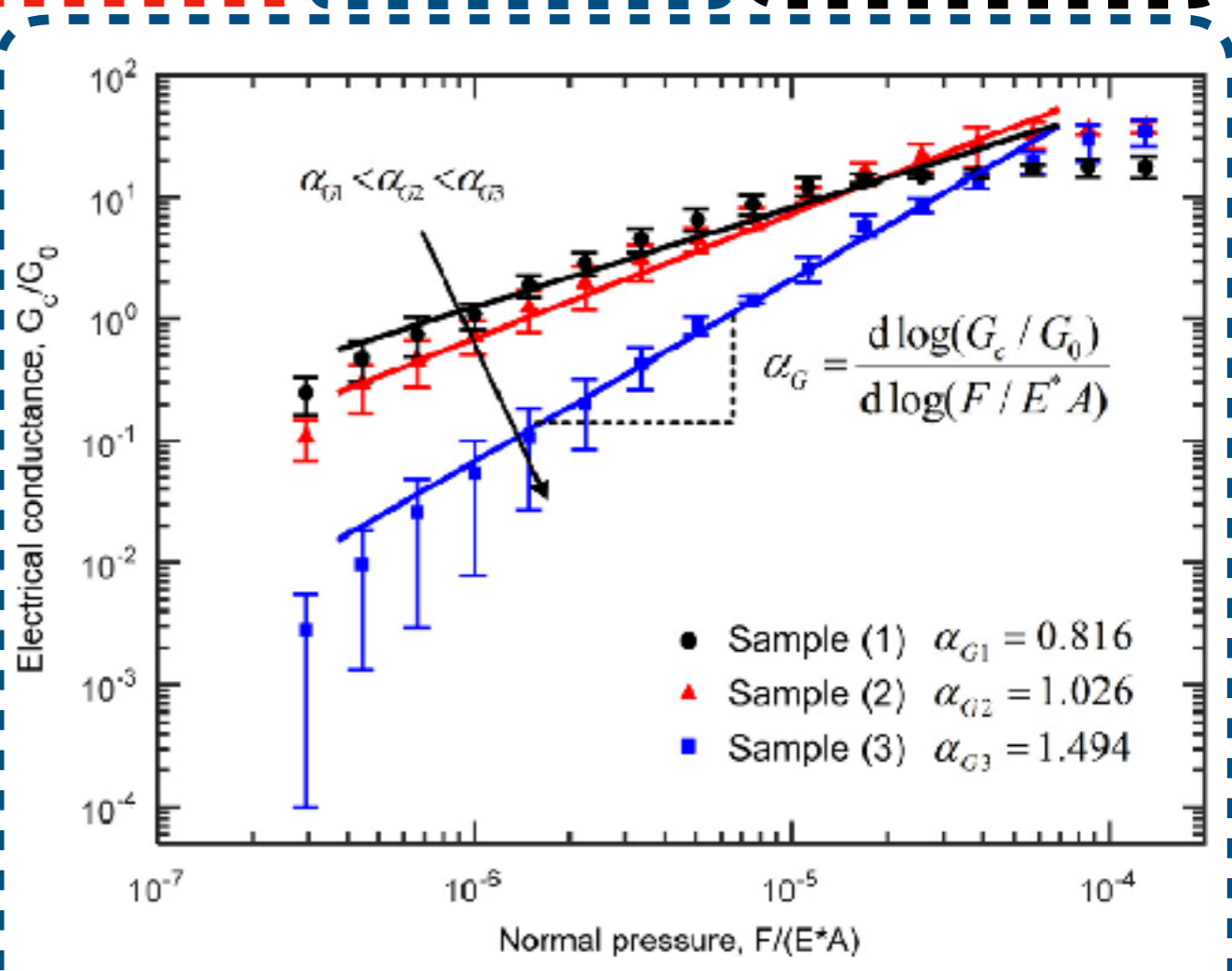
Contact stiffness and electrical contact resistance

Sample surface characteristics for different surface treatments.

Sample type	RMS roughness/ μm	Fractal dimension, D_f	RMS slope	Contact stiffness, α_E	Electrical conductance, α_G	Exponent ratio, α_G/α_E
S1	0.057 ± 0.005	2.093 ± 0.062	0.009 ± 0.001	0.463 ± 0.022	0.816 ± 0.081	1.762 ± 0.194
S2	4.179 ± 0.194	2.551 ± 0.022	0.224 ± 0.015	0.569 ± 0.029	1.026 ± 0.049	1.803 ± 0.126
S3	2.970 ± 0.276	2.626 ± 0.017	0.202 ± 0.010	0.605 ± 0.022	1.494 ± 0.134	2.469 ± 0.239



$$\frac{E_c}{E^*} \propto \left(\frac{F}{E^*A} \right)^{\alpha_E}$$

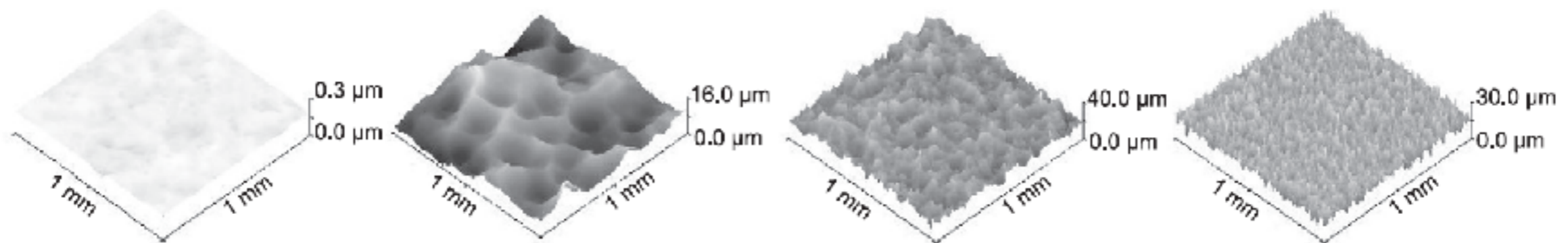


$$\frac{G_c}{G_0} \propto \left(\frac{F}{E^*A} \right)^{\alpha_G}$$

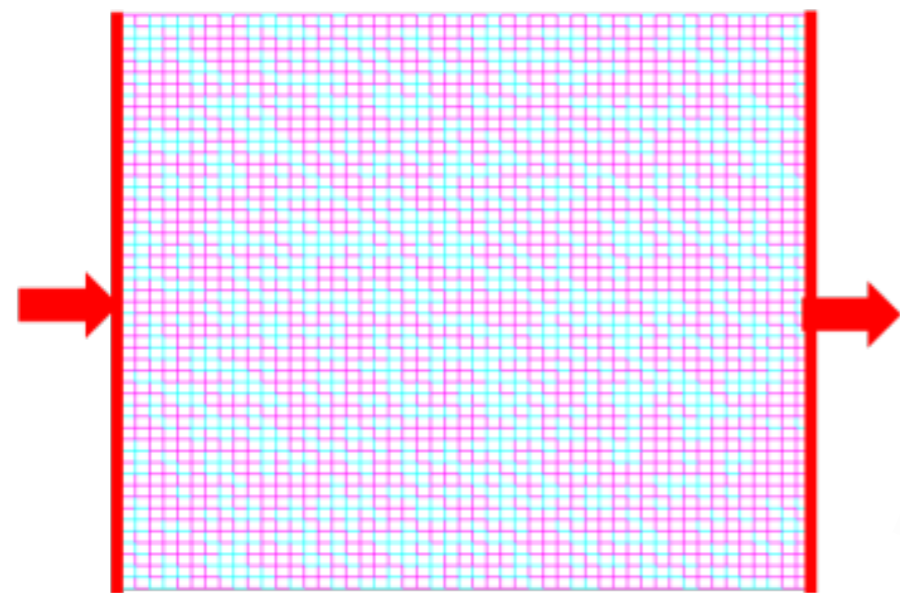
Measurement data

- **Surface morphological data:** six types of surfaces (polished, SMAT, shot-peening) with distinct combination of roughness measures. Each sample with multiple 1mm x 1mm scans.
- **Contact stiffness measurement,** six types of surfaces tested across a wide range of compressive stress (~five magnitudes).
- **Electrical contact resistance measurement,** three types of samples tested across three magnitudes of applied stress.

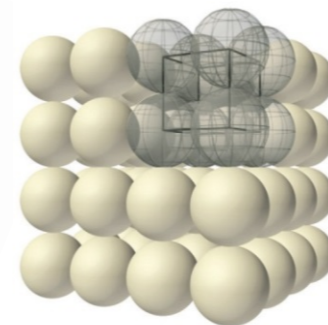
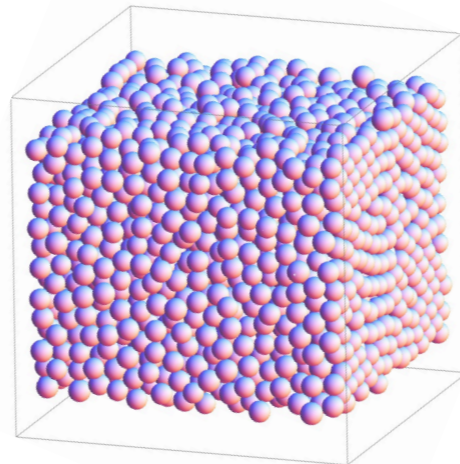
Ideal for contact mechanics model calibration. Full experimental data set is available online, request via yixiang.gan@sydney.edu.au.



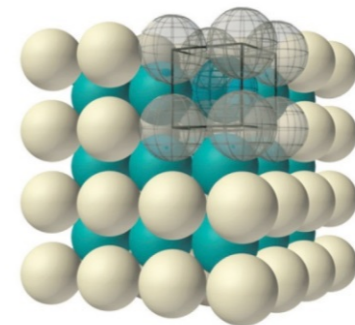
RC network and frequency responses



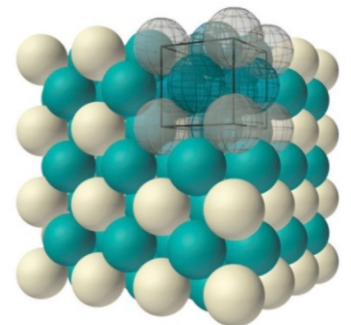
2D vs 3D; random vs lattice



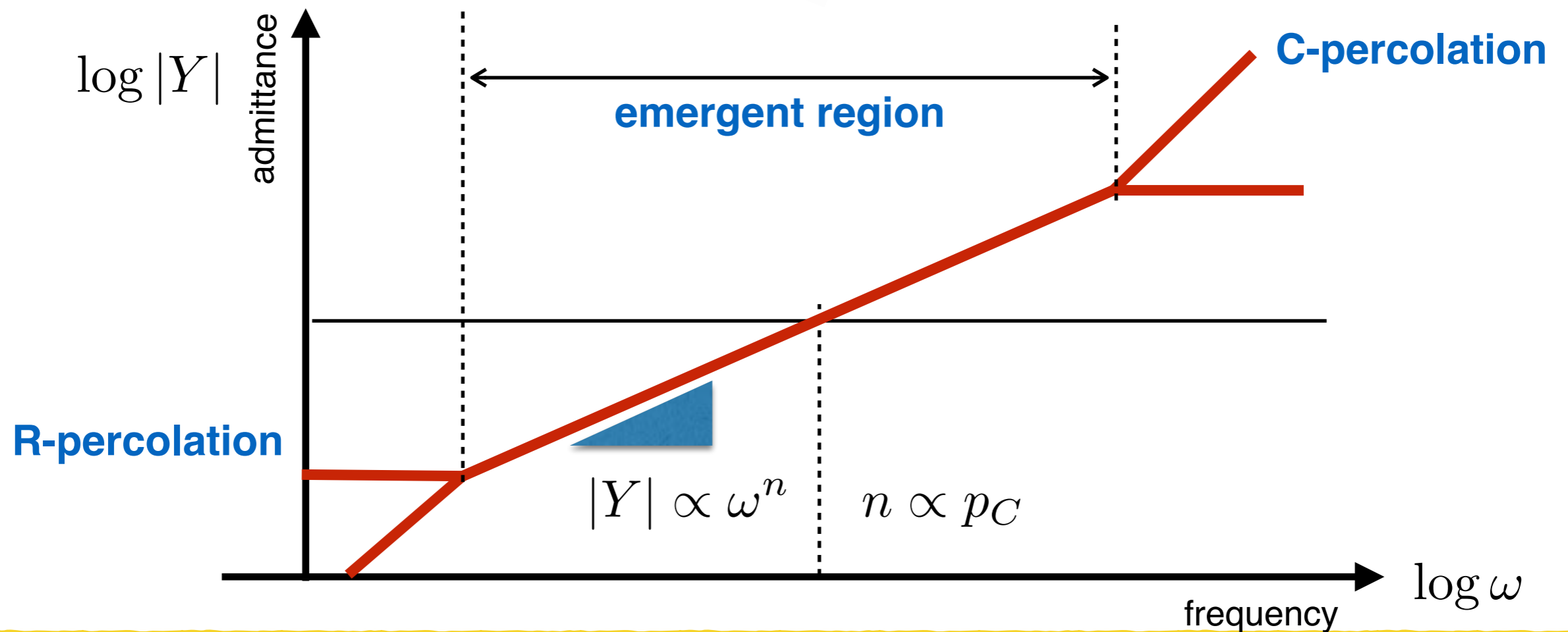
(a) Simple cubic



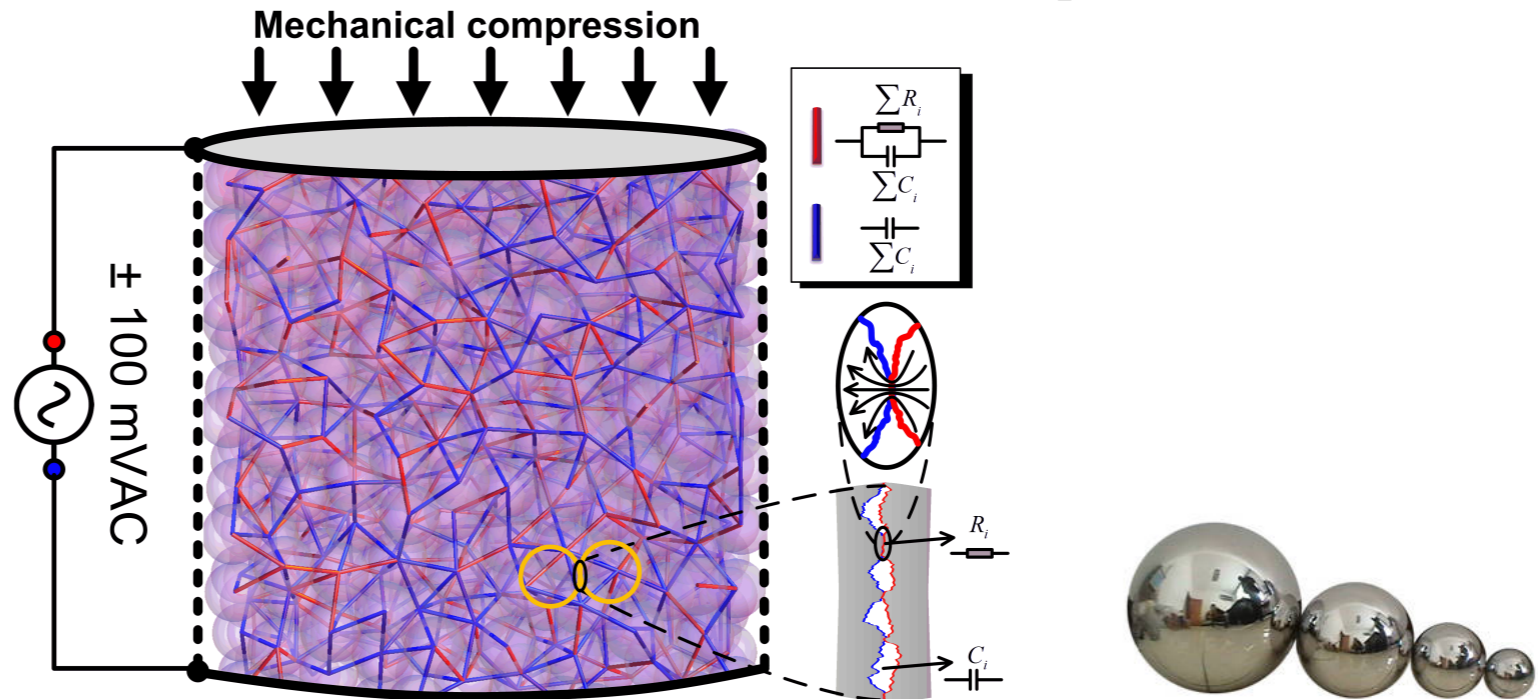
(b) Body-centered cubic



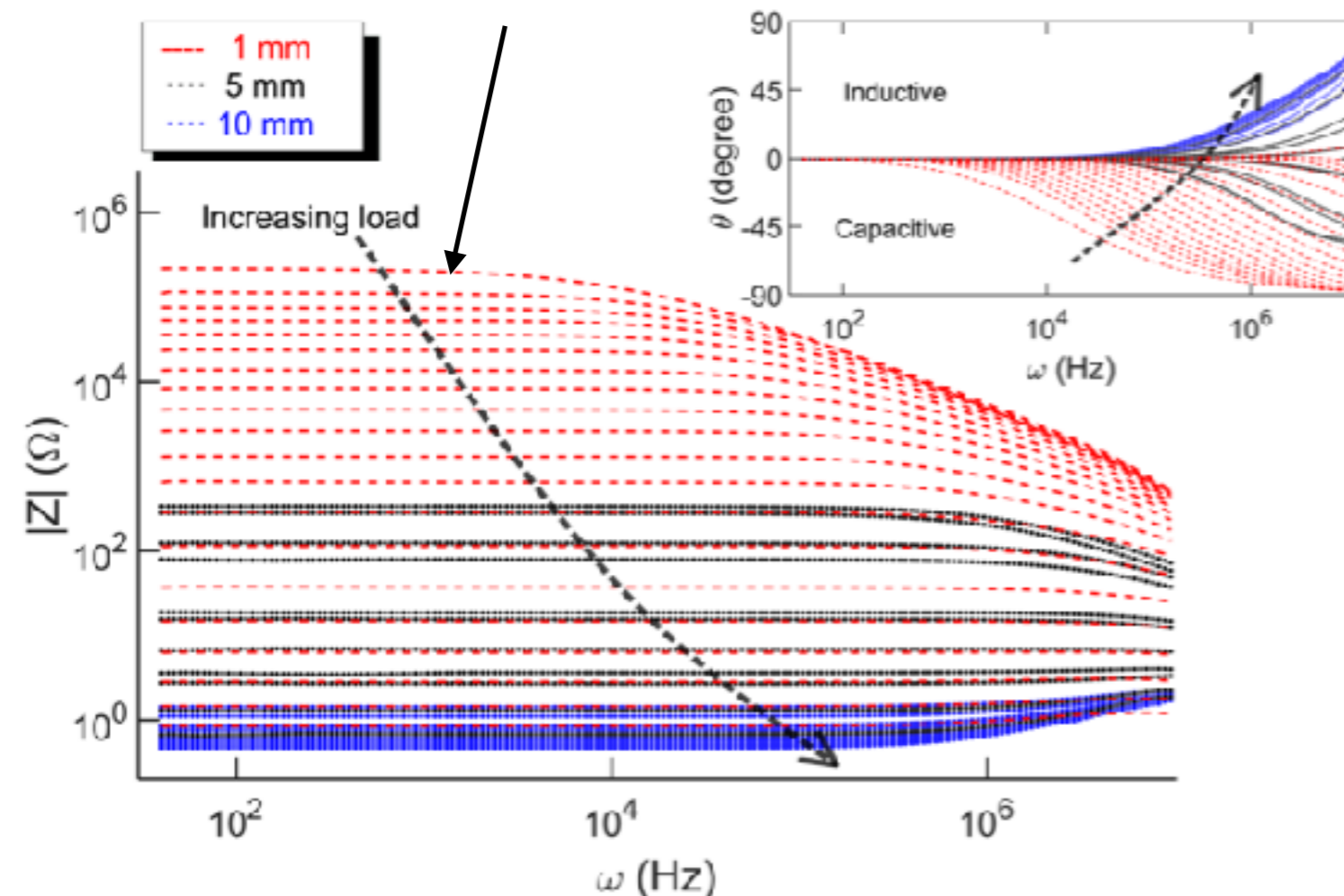
(c) Face-centered cubic



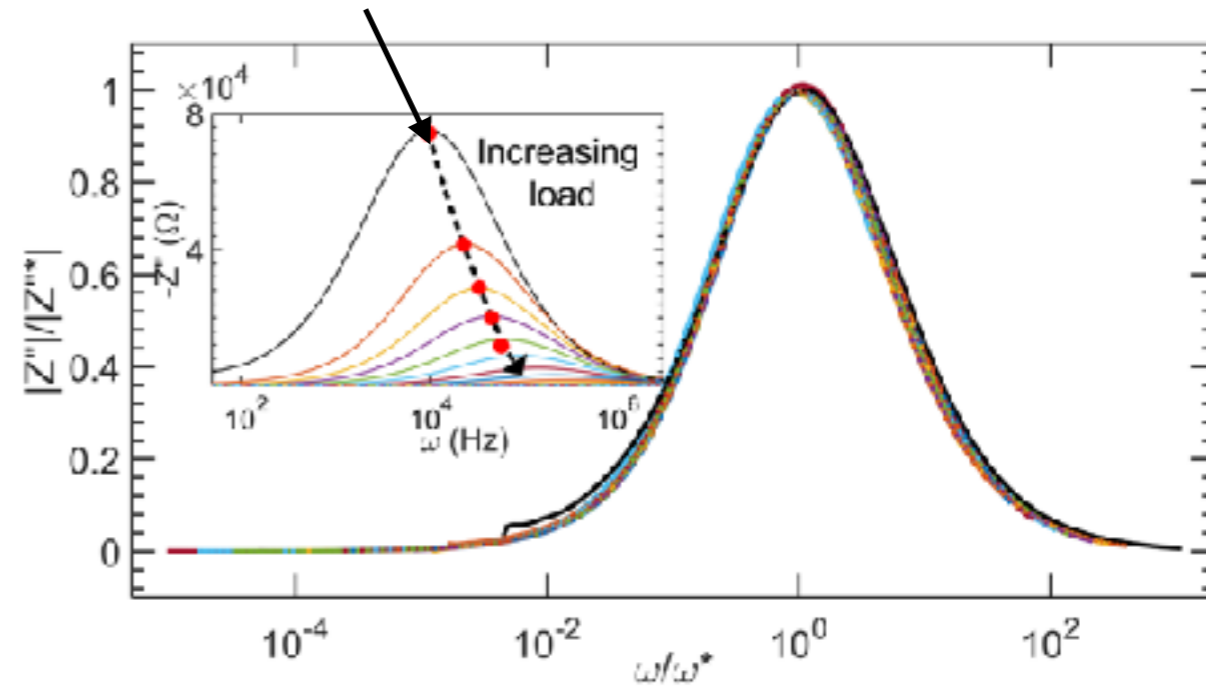
Stress-dependent electrical conduction: Experiments



characteristic resistance

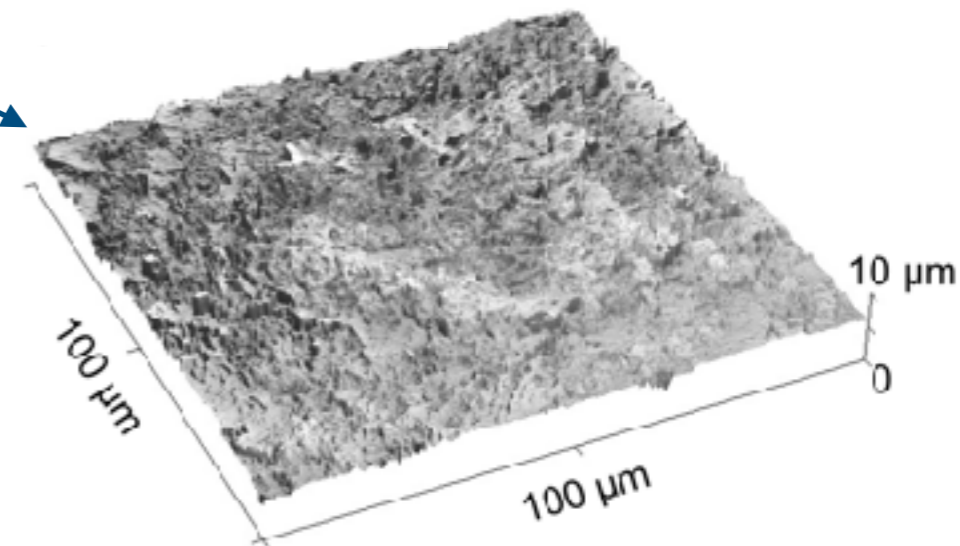
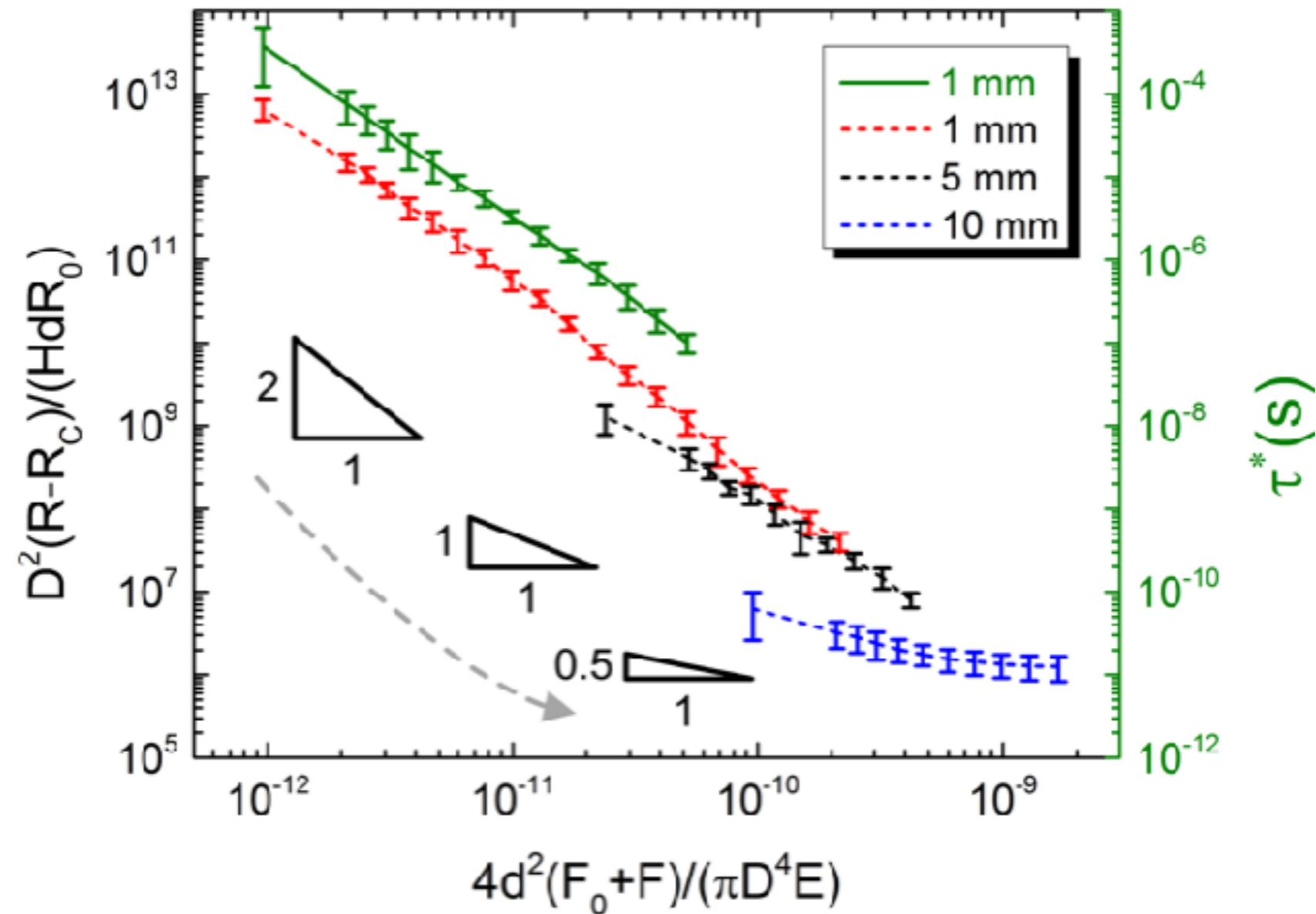


characteristic frequency



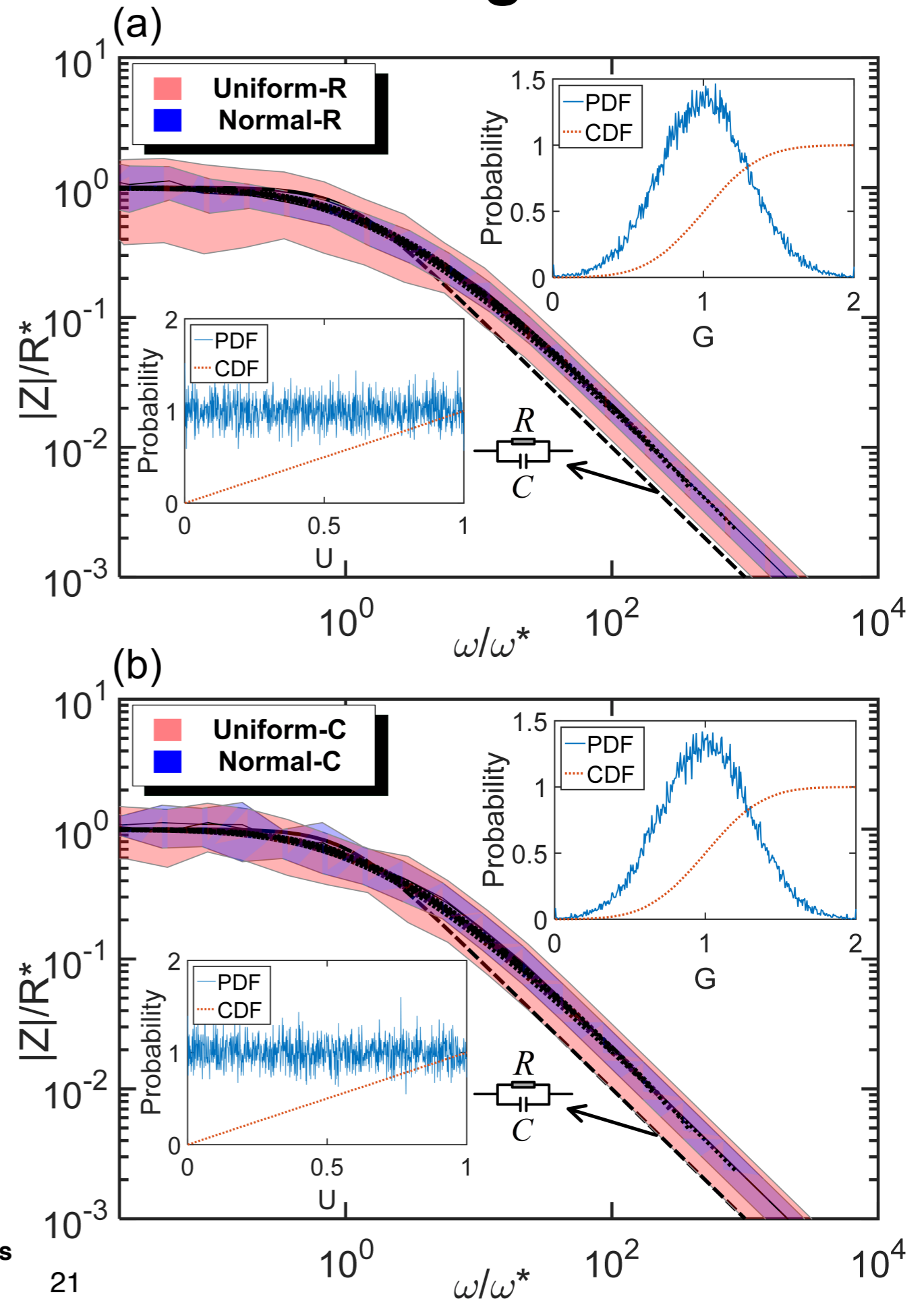
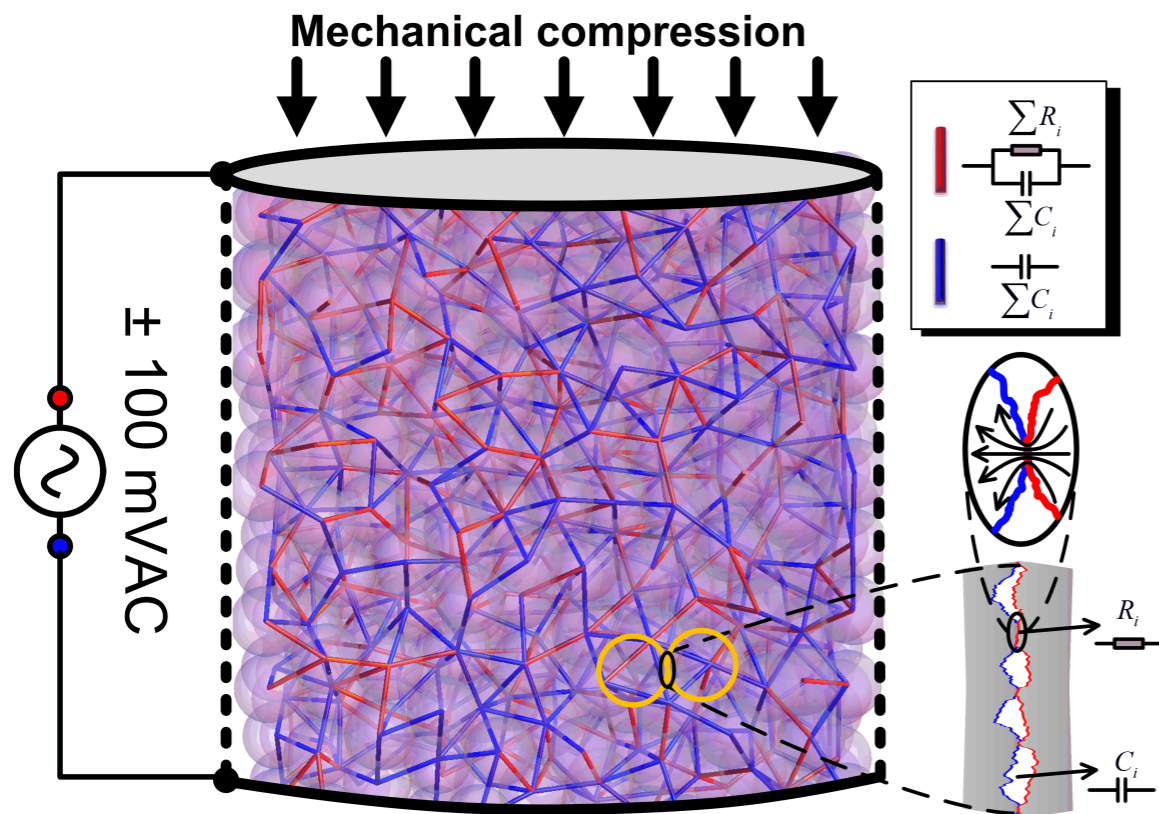
finite random binary percolation networks. **PLoS ONE** 12(2): e0172298.
 Zhai, C., Gan, Y., Hanaor, D., Proust, G. (2018) Stress-dependent electrical transport and its universal scaling in granular materials. **Extreme Mechanics Letters** (under revision).

Stress-dependent characteristic resistance and frequency



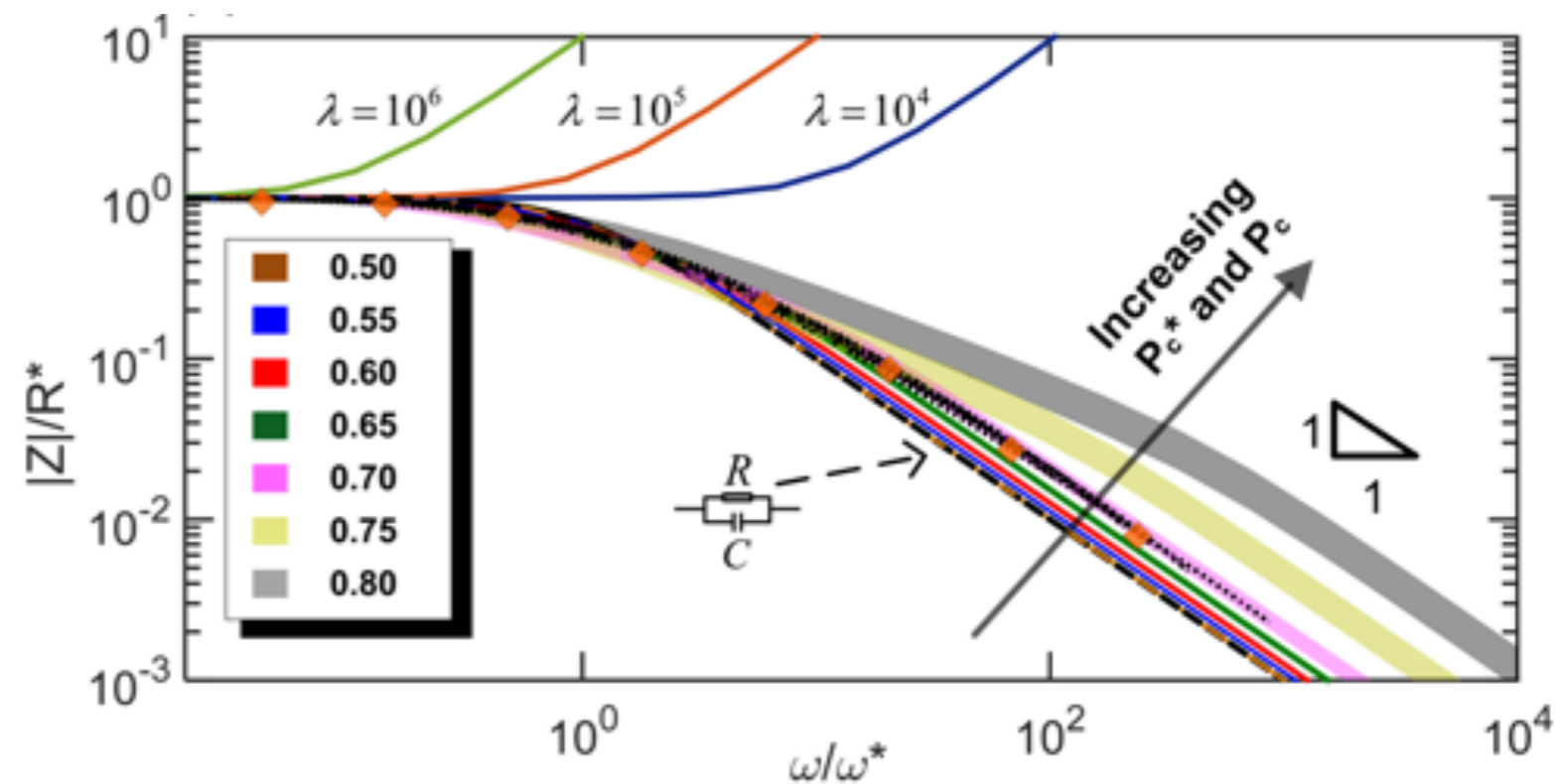
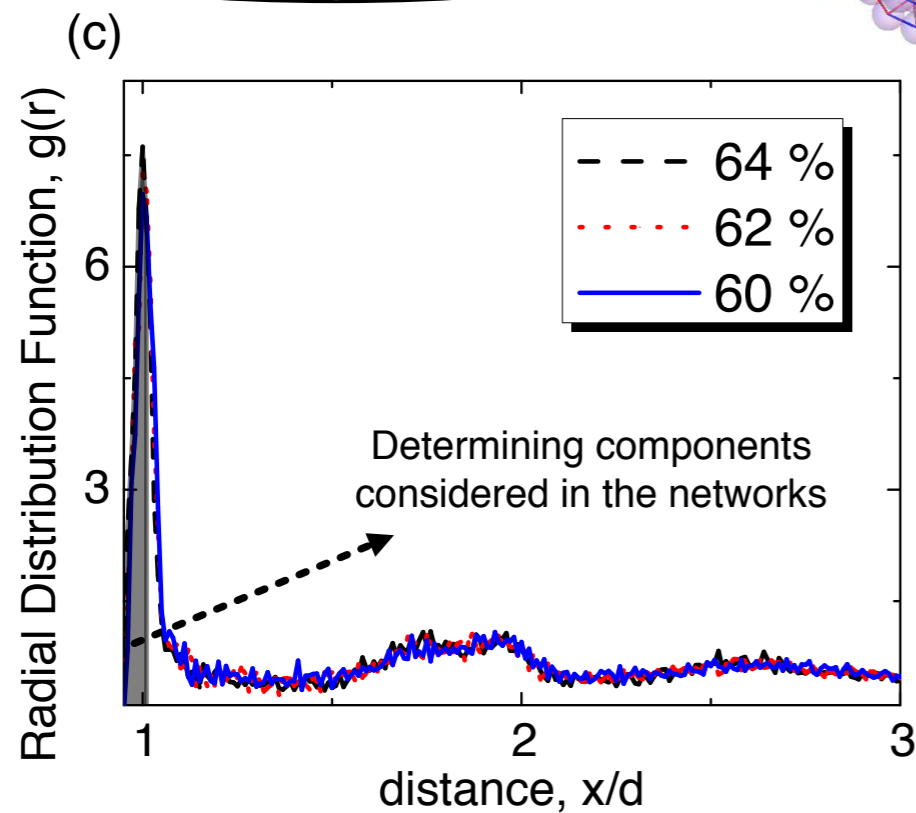
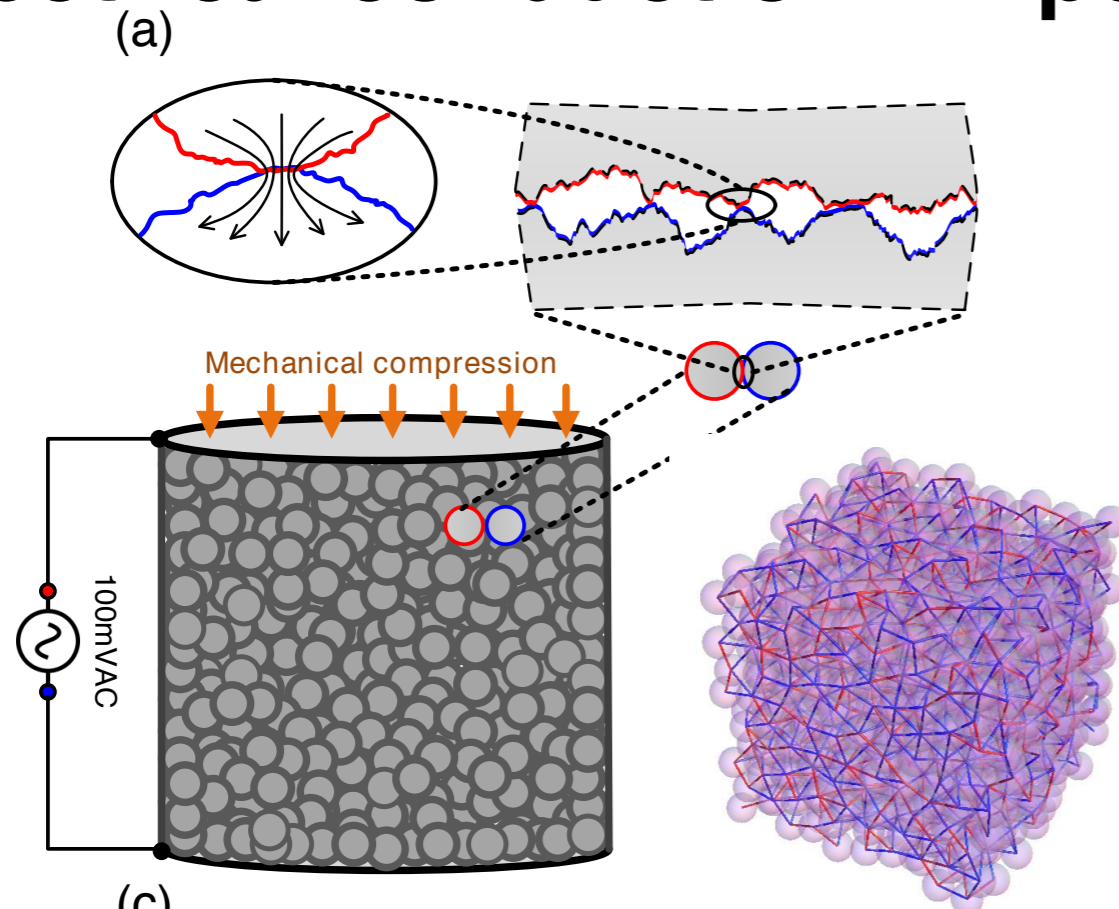
Zhai, C., Gan, Y., Hanaor, D., Proust, G. (2018) Stress-dependent electrical transport and its universal scaling in granular materials. **Extreme Mechanics Letters** (under revision).

Electrical conduction: RC network modelling



Zhai, C., Hanaor, D., Gan, Y. (2017) Universality of the emergent scaling in finite random binary percolation networks. **PLoS ONE** 12(2): e0172298.
 Zhai, C., Gan, Y., Hanaor, D., Proust, G. (2018) Stress-dependent electrical transport and its universal scaling in granular materials. **Extreme Mechanics Letters** (under revision).

Electrical conduction: Experiments vs Simulation

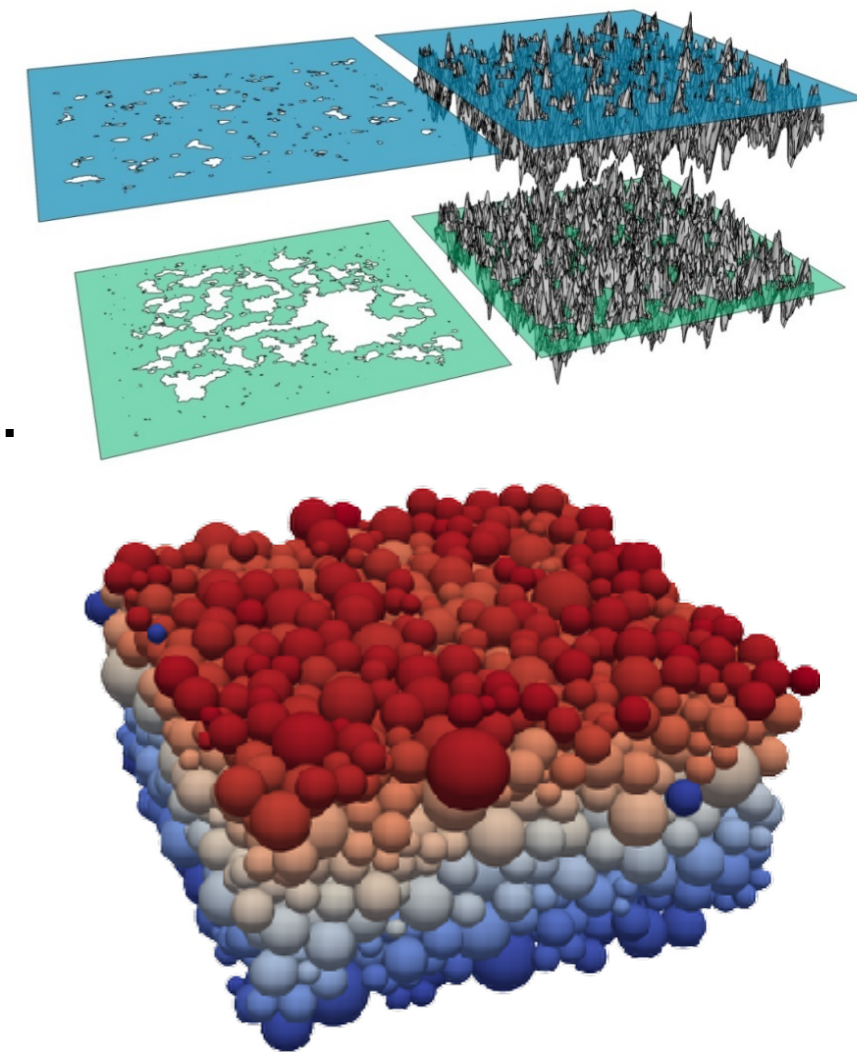


Zhai, C., Hanaor, D., Gan, Y. (2017) Universality of the emergent self-organized finite random binary percolation networks. **PLoS ONE** 12(2): e0172298.

Zhai, C., Gan, Y., Hanaor, D., Proust, G. (2018) Stress-dependent electrical transport and its universal scaling in granular materials. **Extreme Mechanics Letters** (under revision).

Conclusions

- **At rough surfaces (contact mechanics),**
 - Contact stiffness and electrical contact resistance.
 - Stress-dependent power-law behaviour, both mechanical and electrical responses.
 - Correlations to the surface roughness measurement (e.g., fractal dimension).
- **In granular packing (complex network),**
 - Effective RC responses under compression, stress-dependent power-law behaviour.
 - Observed stress-induced phase transition.
 - Universal scaling law.



Thank you!



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