Novel High k Application Workshop

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Nanoscale characterization of high-k dielectrics by electrical SPM methods

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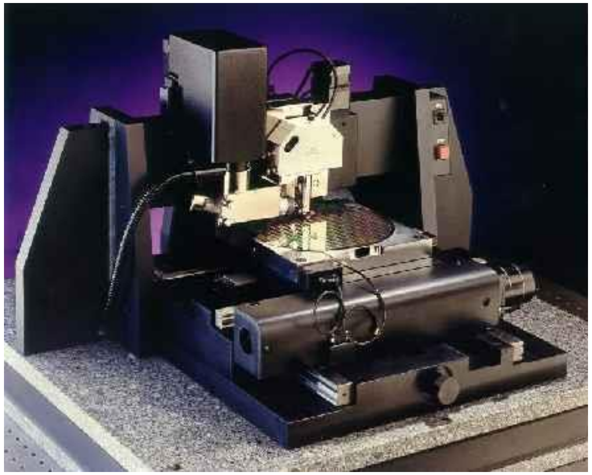
Nanoscale characterization of high-k dielectrics by electrical SPM methods

- **SPM equipment at Fraunhofer IISB**
  - Bruker Dimension Icon and DI 5000 with NanoScope V controller
  - cAFM, TUNA, and extended TUNA (SCM, SSRM) modules
  - for all electrical SPM measurements, commercially available PtIr (EFM) tips are used
  - all measurements in ambient conditions (no UHV or N_2)

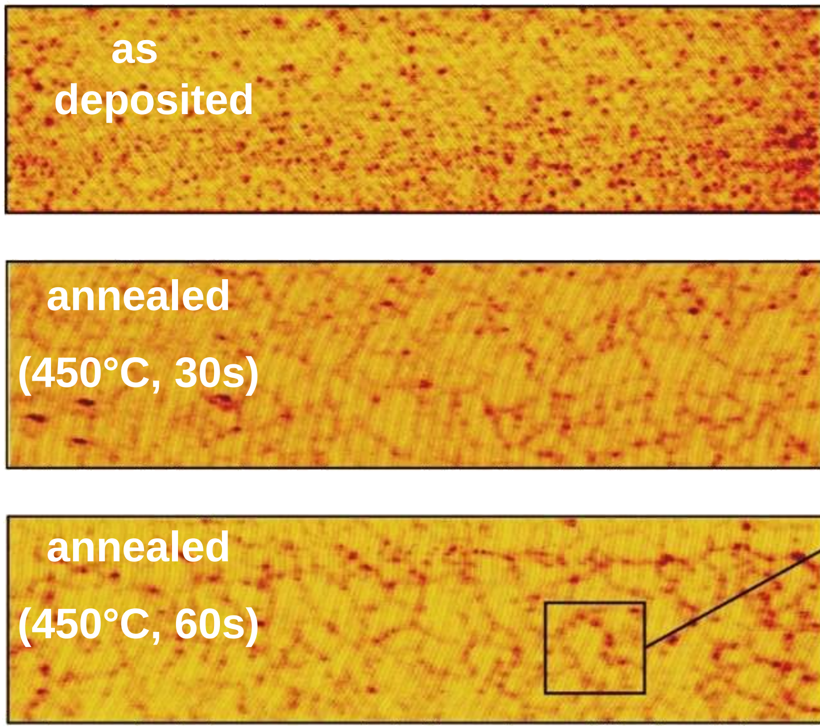


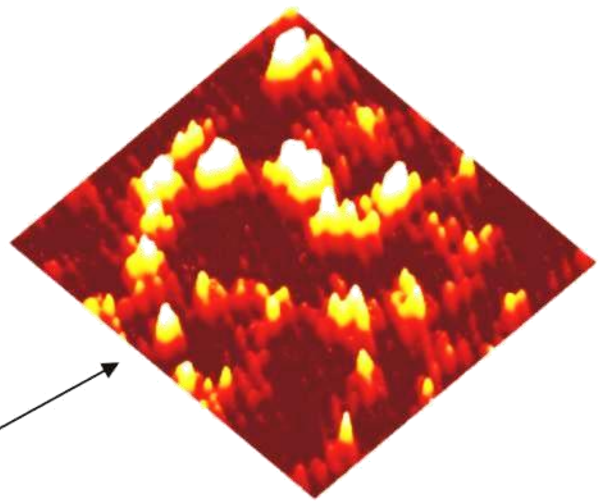
http://www.bruker.com, http://nanoscaleworld.bruker-axs.com

Nanoscale characterization of high-k dielectrics by electrical SPM methods

- **the charm of electrical SPM is its imaging capability on the nanoscale**
  - identification of the main leakage current paths of a sample by cAFM maps
  - ZrO_2 ALD films (5 nm) on native oxide (≈1 nm) on p-type silicon

cAFM current maps:
scan area: 2000 nm x 500 nm,
applied bias voltage: -2.7 V,
current scale: -2.5 pA to 2.5 pA



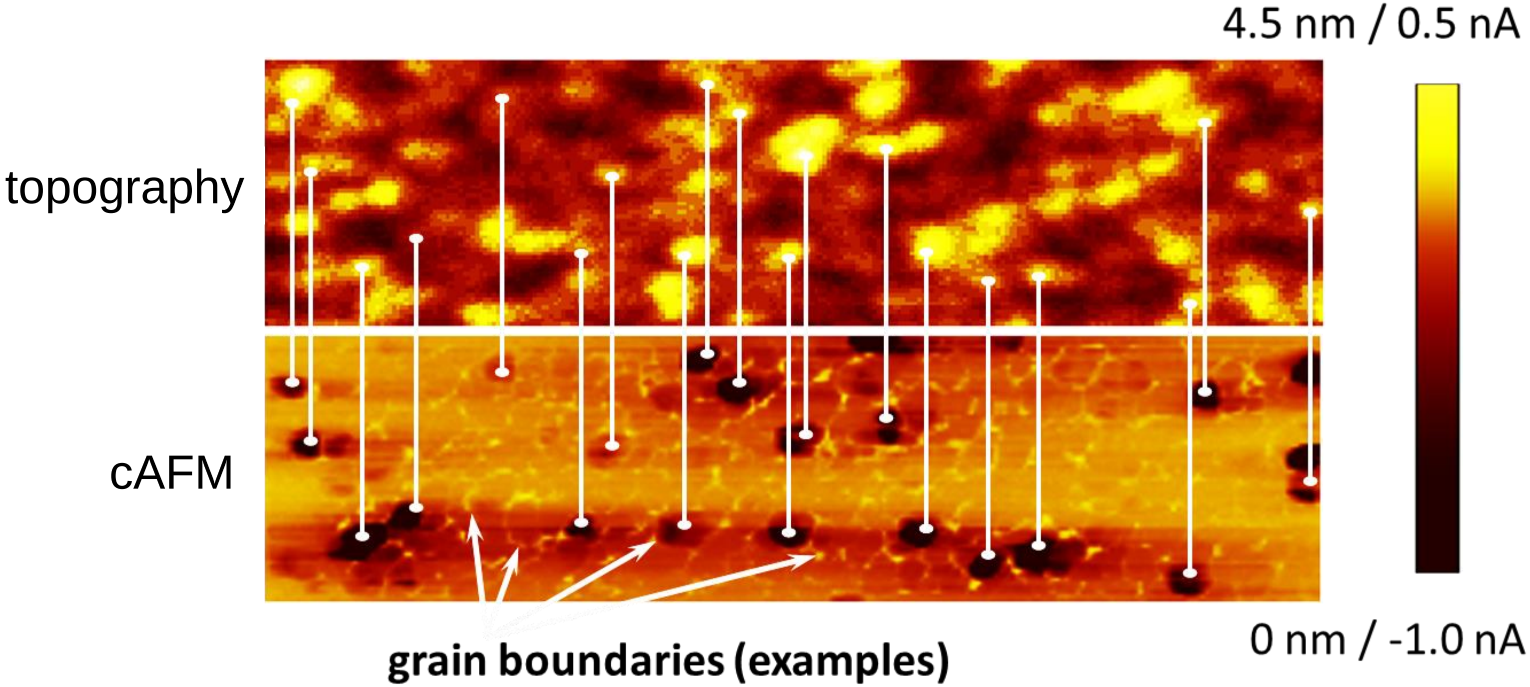


3D detail view of granular feature (rotated by 45 degrees, different current scale: 0 pA (dark) to +3 pA (bright))

V. Yanev et al., Applied Physics Letters **92**, 252910-1-3 (2008)

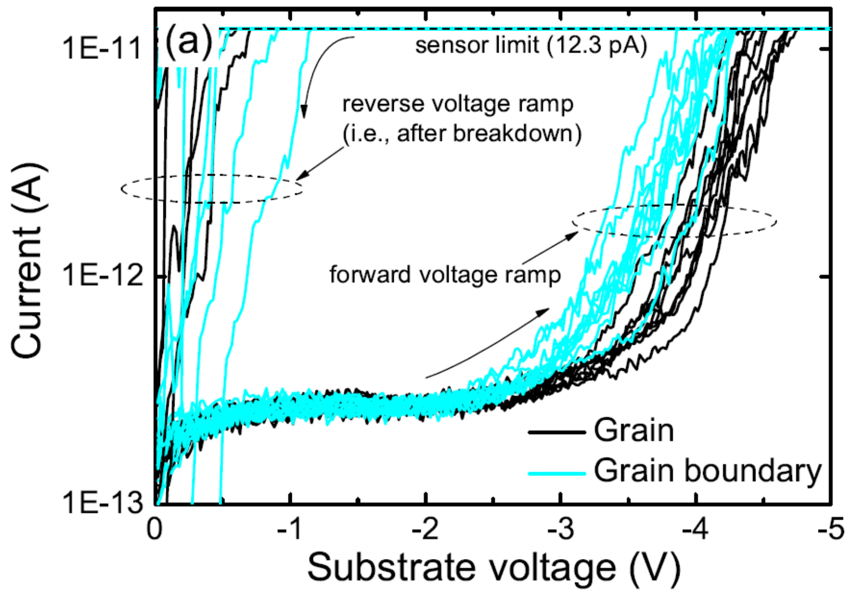
Nanoscale characterization of high-k dielectrics by electrical SPM methods

- **the charm of electrical SPM is its imaging capability on the nanoscale**
  - identification of the main leakage current paths of a sample by cAFM maps
  - is it along grain boundaries or through grains?
  - 20 nm TiO_2 ($TiCl_4$-ALD) on 25 nm RuO_2 + PDA (400 °C, O_2/N_2)



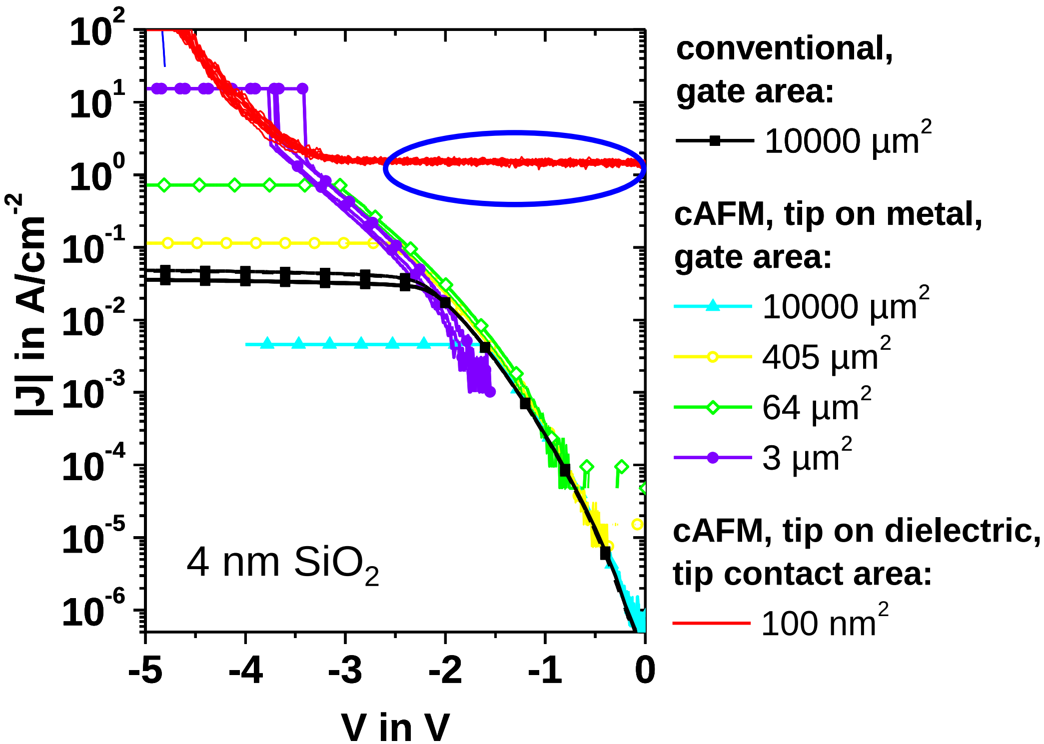
K. Murakami et al., ACS Applied Materials & Interfaces **6**, 2486-2492 (2014)

- **However, electrical SPM can and should do more ……**
  - SPM allows for complementary / in-depth information due to its lateral resolution (e.g., local I-V at grain boundaries or through grains for ZrO_2)



K. Murakami et al., AIP Conference Proceedings **1395**, 134-138 (2011)

- **However, electrical SPM can and should do more ……**
  - still, though, its corresponding capabilities are not sufficiently exploited or even explored, partly due to:
  - insufficient sensitivity of cAFM for fully exploiting current conduction mechanisms
  - insufficient repeatability and reproducibility
  - …

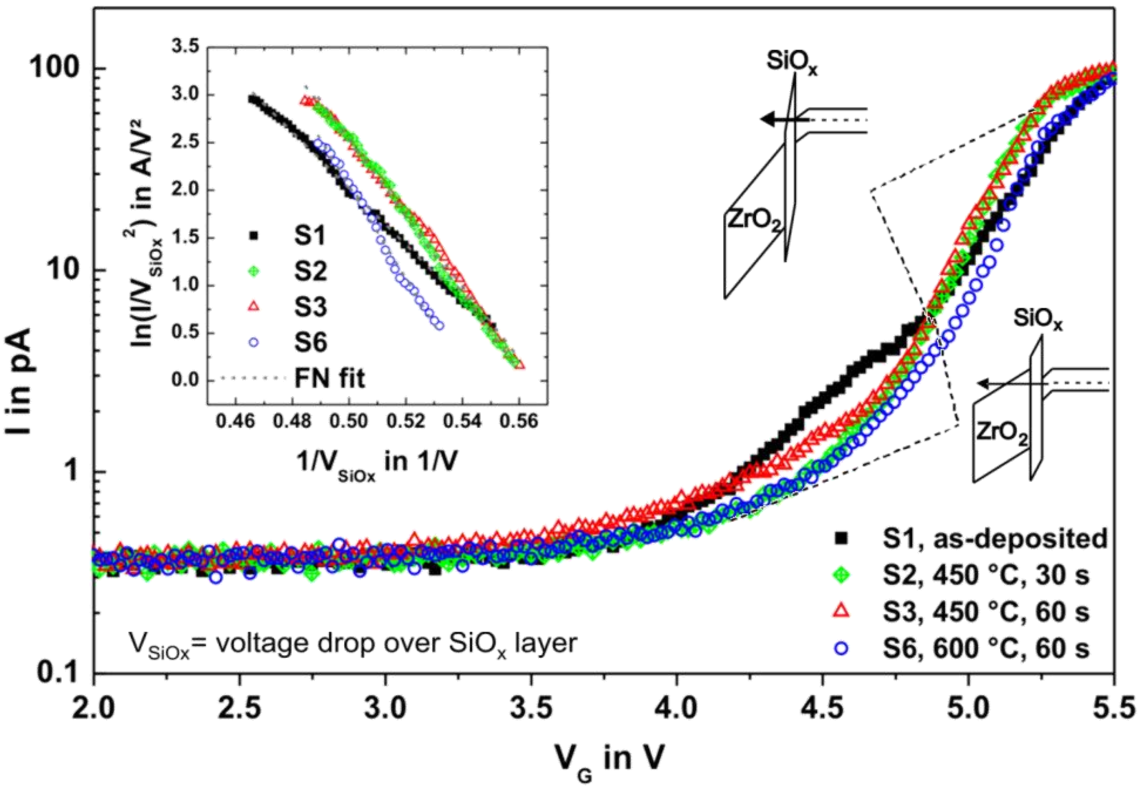


M. Rommel et al., Journal of Vacuum Science & Technology B **31**, 01A108 (2013)

Outline

- Selected examples for quantification of electrical SPM results or the direct correlation of such results with conventional methods
- Thickness mapping of high-k dielectrics
- Summary and outlook

- **Quantification of electrical SPM**
  - $ZrO_2/SiO_x/Si$ stack: determination of SiO_x layer thickness from local I-V

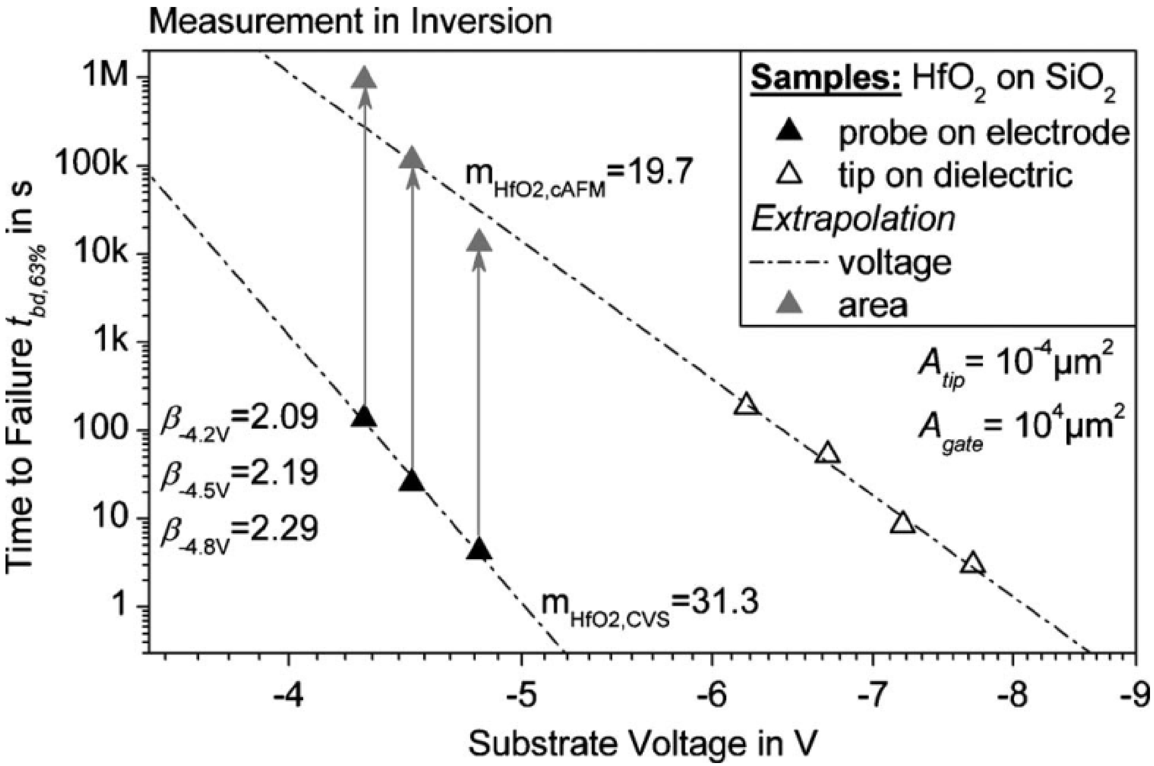


	cAFM	TEM
	t_{SiOx} [nm]	t_{SiOx} [nm]
as-dep.	1.06	1.1
S2	1.16	1.1-1.2
S6	1.30	1.3-1.4

A. Paskaleva et al., Journal of Applied Physics **104**, 024108-1-7 (2008)

- **Quantification of electrical SPM**
  - TDDB evaluation using CVS: comparing cAFM and conventional methods

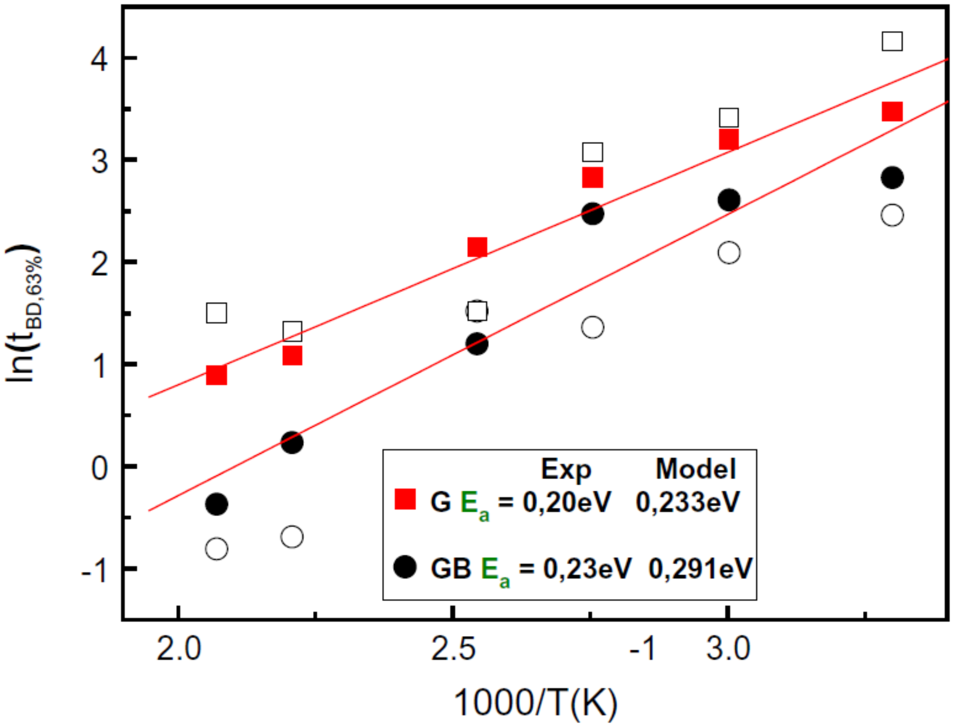
    4 nm SiO_2 + 4 nm MOCVD HfO_2, PDA: 600 °C in O_2



T. Erlbacher et al., Journal of Vacuum Science & Technology B **29**, 01AB08 (2011)

Nanoscale characterization of high-k dielectrics by electrical SPM methods

- **Quantification of electrical SPM**
  - in depth evaluation of temperature dependent TDDB (CVS @ 30 °C …210 °C)
  - 5 nm HfO_2 (ALD) / 1 nm SiO_x interfacial layer, PDA: 1000 °C, N_2
  - bimodal character due to measuring on both, grains (G) and grain boundaries (GBs)
  - from Arrhenius plot similar activation energies for Gs and GBs TDDB are evaluated
    → breakdown always initiated by SiO_x interfacial layer



V. Iglesias et al., Microelectronic Engineering **109**, 129-132 (2013)

- **Thickness mapping of high-k dielectrics**
  - SCM does NOT allow quantitative capacitance measurements!
  - so far, only possible by dedicated home-made equipment using CV measurements (12-24 hours for each measurement!!)*
  - recently, scanning microwave microscopy (SMM) has been introduced for attofarad capacitance measurements**

    ⇒ using a network analyzer for characterization

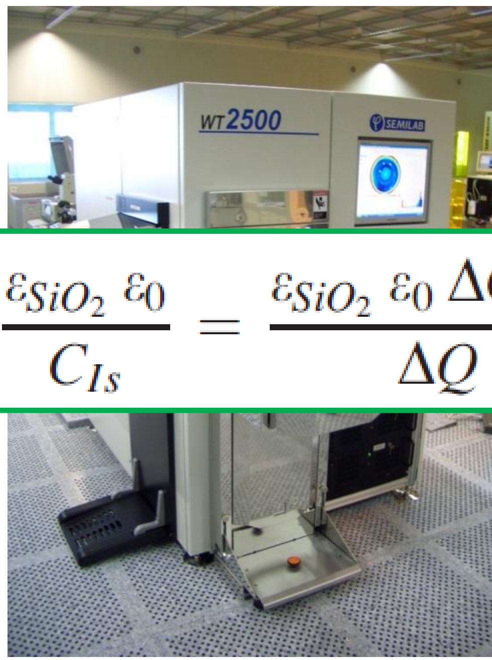
    ⇒ calibration required for quantitative measurements

    ⇒ on-sample calibration procedures developed***

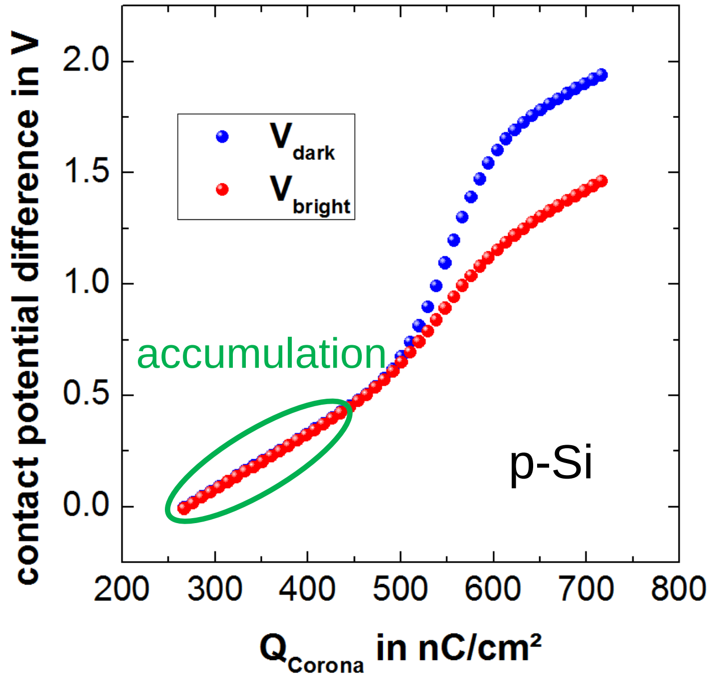
* W. Brezna et al., Applied Physics Letters **83**, 4253-4255 (2003)
** Agilent Technologies, Attofarad Capacitance Measurement with Scanning Microwave Microscopy, application note, 2010
*** G. Gramse et al., Nanotechnology **25**, 145703-1 – 145703-8 (2014)

Nanoscale characterization of high-k dielectrics by electrical SPM methods

- **Thickness mapping of high-k dielectrics using an alternative approach**
  - Corona charging and subsequent Kelvin probe force microscopy (KPFM)
    → adaptation of and comparison with
    → conventional macroscopic “V-Q” method (Semilab WT-2500, 8 mm SKP)



$$EOT = \frac{\varepsilon_{SiO_2}\,\varepsilon_0}{C_{Is}} = \frac{\varepsilon_{SiO_2}\,\varepsilon_0\,\Delta CPD}{\Delta Q}$$



J. Trapnauskas et al., Applied Physics Letters **104**, 052907-1-4 (2014)

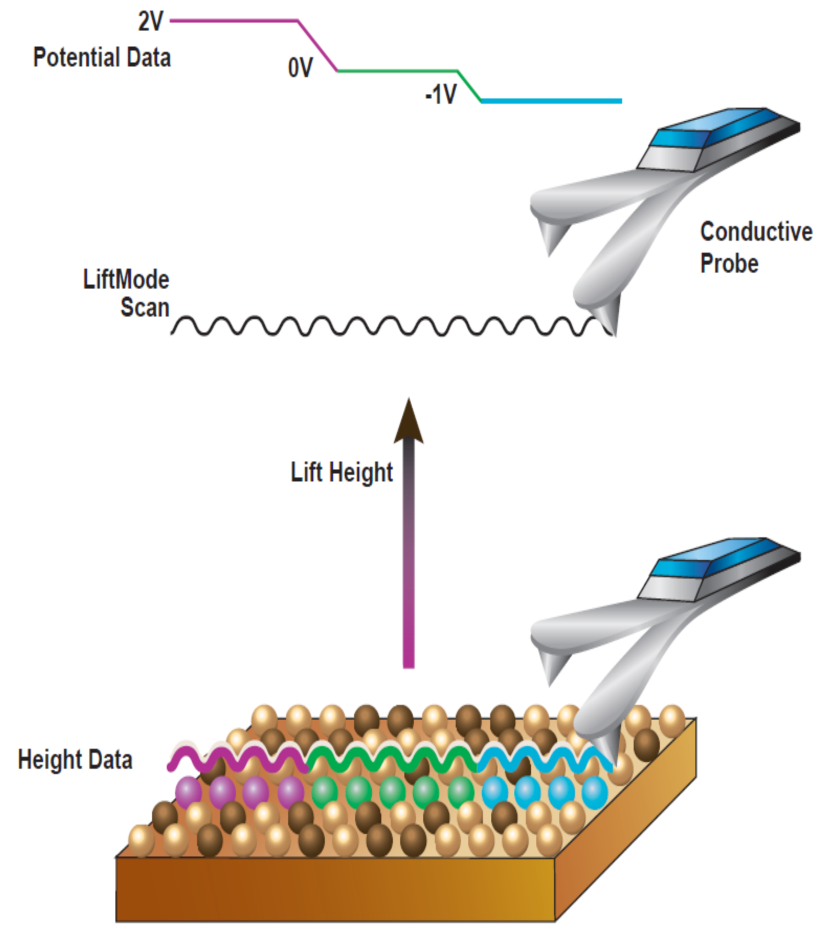
Nanoscale characterization of high-k dielectrics by electrical SPM methods

- **Thickness mapping of high-k dielectrics using an alternative approach**
  - procedure
    - ⇒ charging in clean room
    - ⇒ KPFM in SPM lab
  - important to note:
    - ⇒ simple KPFM implementation

      two steps:

      a) topography

      b) CPD in lift mode (10 nm)
    - ⇒ ambient conditions

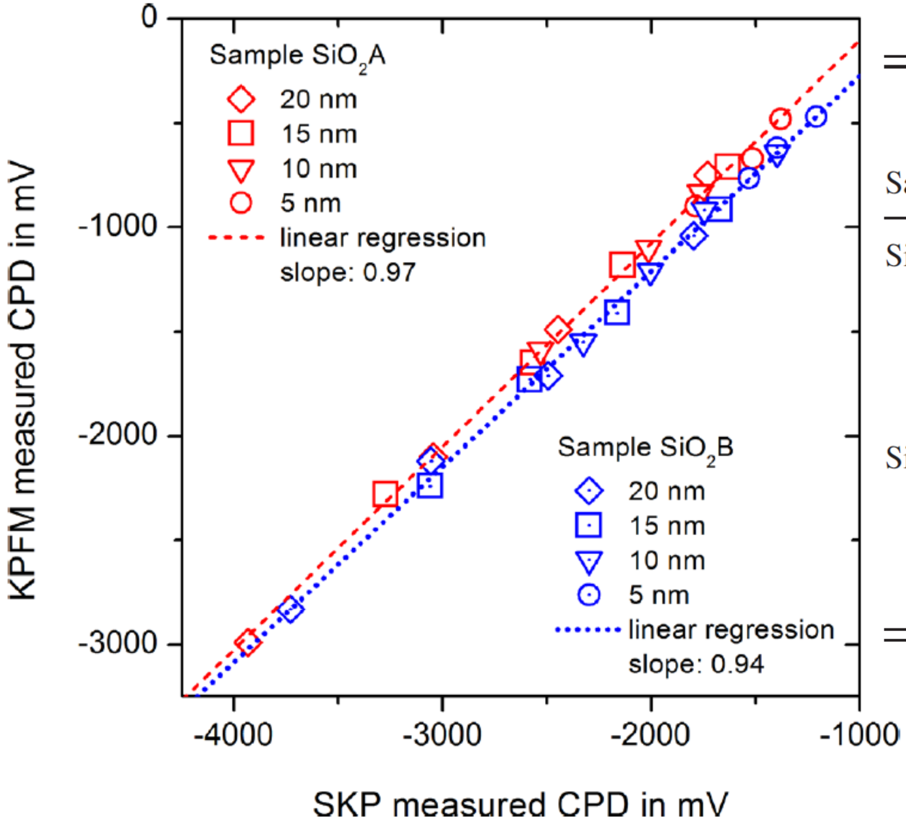


J. Trapnauskas et al., Applied Physics Letters **104**, 052907-1-4 (2014)

http://www.brukerafmprobes.com/download/BrukerProbeCat_2013_International_LowFinal.pdf, 22.03.2014

Nanoscale characterization of high-k dielectrics by electrical SPM methods

- **Thickness mapping of high-k dielectrics using an alternative approach**
  - proof of concept using SiO_2 sample with stripes of different SiO_2 thicknesses



	Thickness (nm)			
Sample	Stripe	SKP	KPFM	Difference (%)
SiO_2A	5	5.3	5.8	9.4
	10	10.0	10.7	7.0
	15	14.9	15.6	4.7
	20	20.9	22.0	5.3
SiO_2B	5	5.1	5.1	0
	10	10.8	10.4	3.7
	15	15.8	14.9	5.7
	20	20.8	20.1	3.4

J. Trapnauskas et al., Applied Physics Letters **104**, 052907-1-4 (2014)

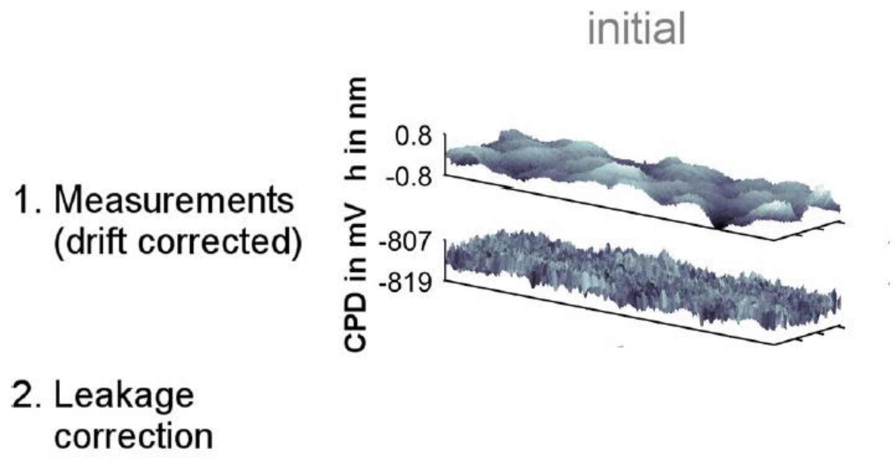
- **Thickness mapping of high-k dielectrics using an alternative approach**
  - for samples with inhomogeneous thicknesses, procedure suffers from insufficient sample positioning accuracy (appr. 1-2 µm possible, but …)
  - an adapted approach is presented which assumes:

    ⇒ correlation between CPD and topography (height)

    ⇒ layer properties do not change substantially within micrometers

J. Trapnauskas et al., Applied Physics Letters **104**, 052907-1-4 (2014)

- **Schematic of the proposed approach**
  - MOCVD 5 nm $HfSi_xO_y$ on 4 nm SiO_2 + RTA (900 °C, 10 s, O_2) + FGA



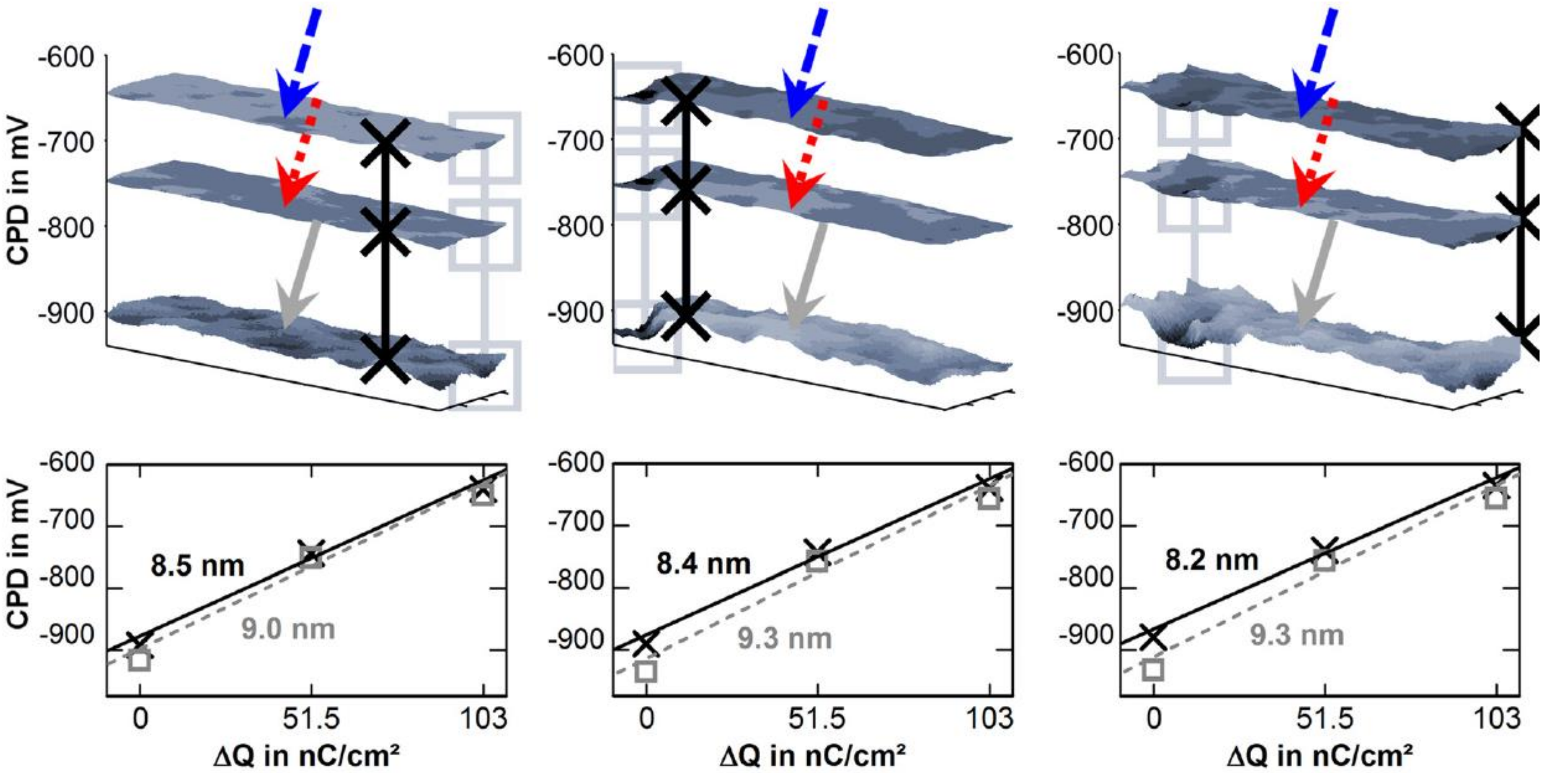
J. Trapnauskas et al., Applied Physics Letters **104**, 052907-1-4 (2014)

Nanoscale characterization of high-k dielectrics by electrical SPM methods

- **Schematic of the proposed approach**

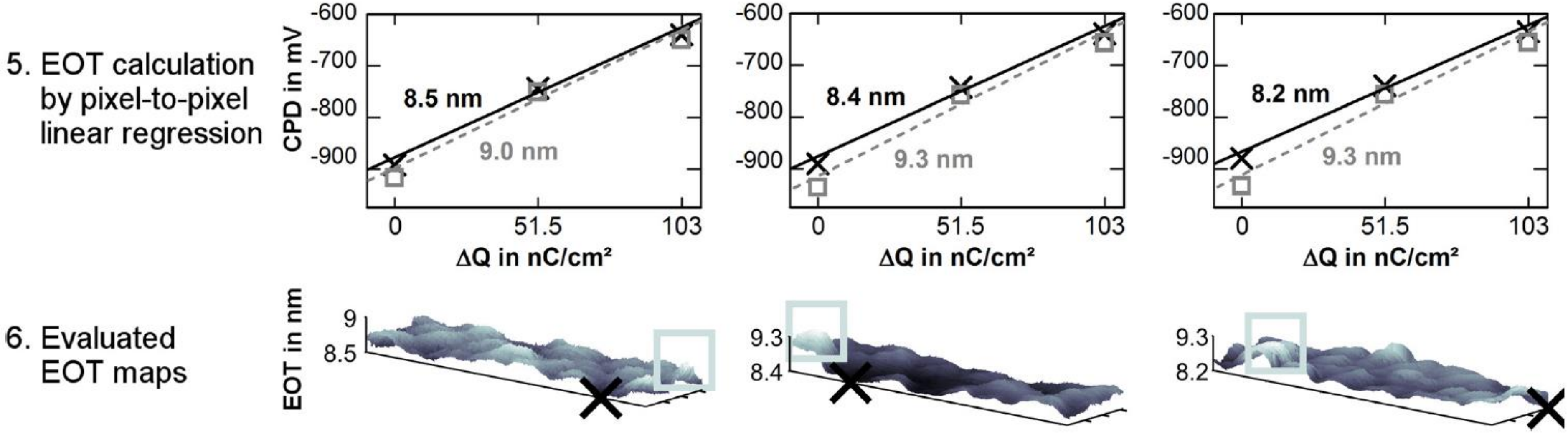
4. Calculation of CPD maps for each height map and each charging step

5. EOT calculation by pixel-to-pixel linear regression



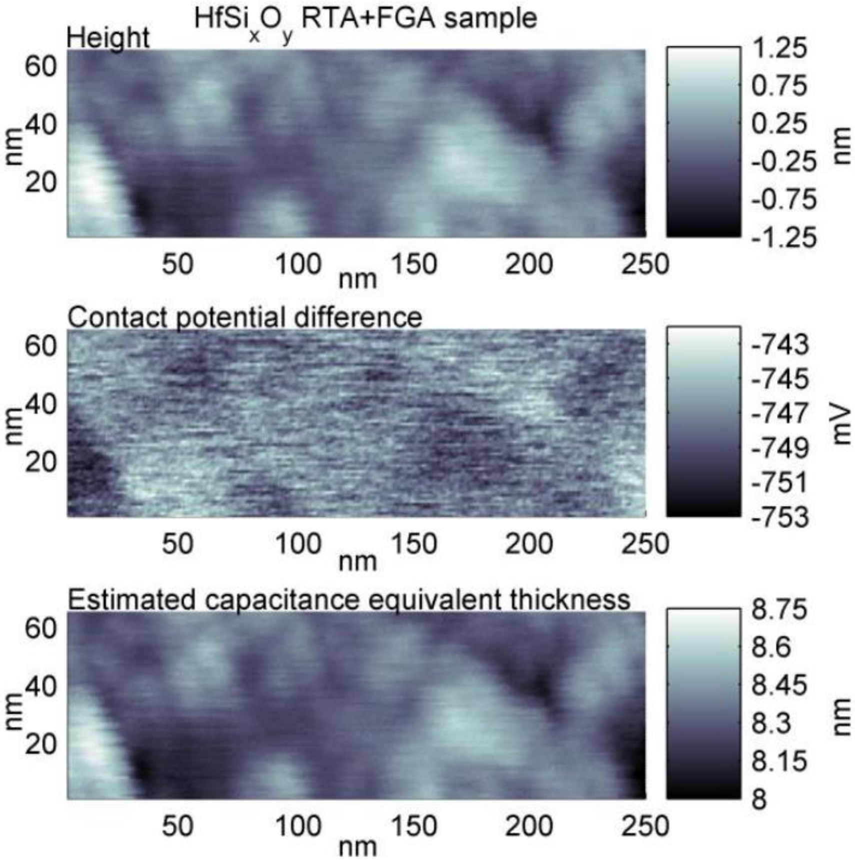
J. Trapnauskas et al., Applied Physics Letters **104**, 052907-1-4 (2014)

- **Schematic of the proposed approach**



J. Trapnauskas et al., Applied Physics Letters **104**, 052907-1-4 (2014)

- **Thickness mapping of high-k dielectrics – results**

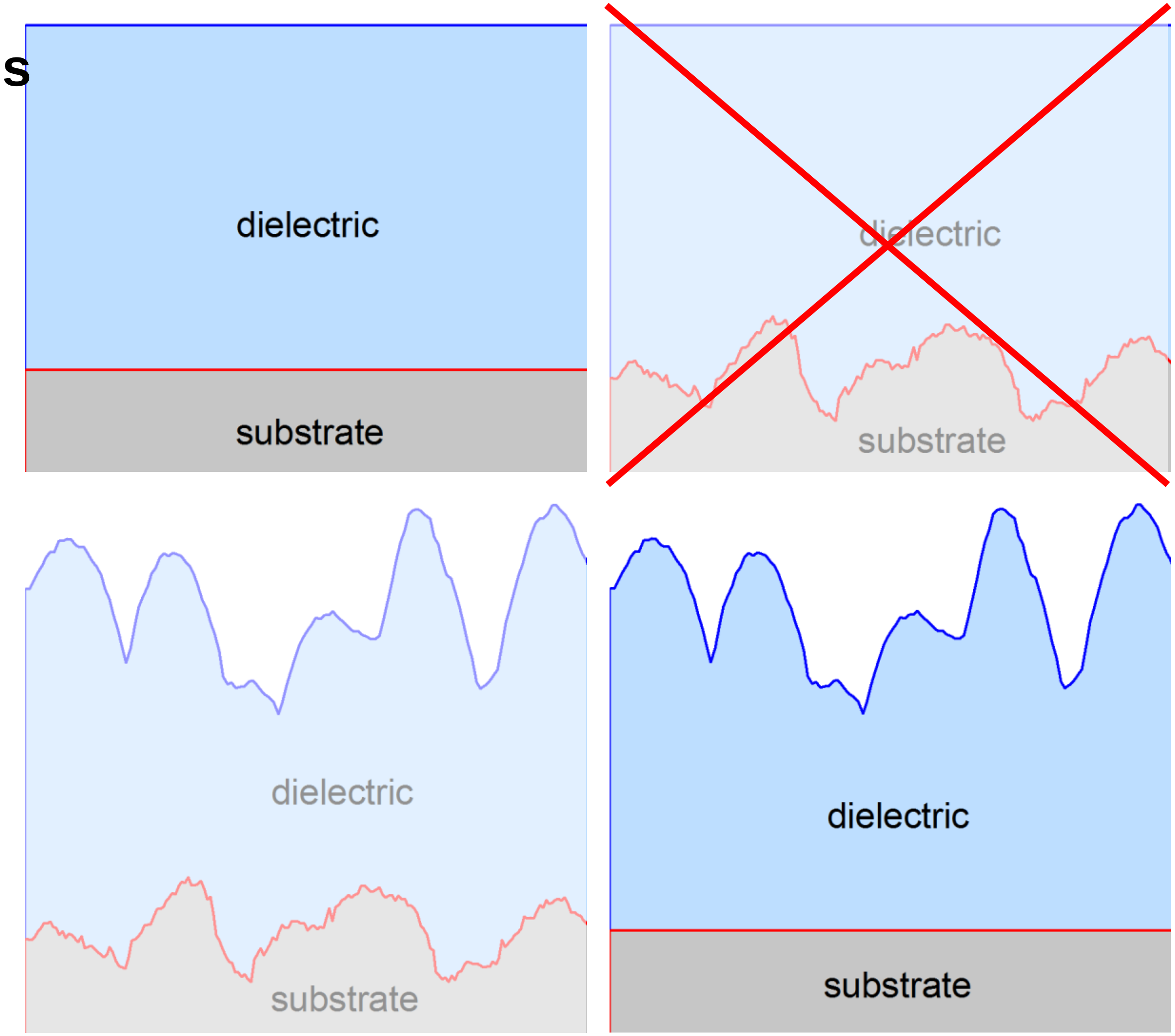


	Thickness (nm)	
Sample	SKP	KPFM
HfO_2	5.3	5.2
$HfSi_xO_y$ RTA	5.7	5.7
$HfSi_xO_y$ RTA + FGA	8.5	8.7

J. Trapnauskas et al., Applied Physics Letters **104**, 052907-1-4 (2014)

Nanoscale characterization of high-k dielectrics by electrical SPM methods

- **Limitations and solutions**
  - flat surfaces but non-homogeneous thickness
    - built-in charging and accurate positioning allows “direct” thickness mapping
    - alternatively, direct charging with SPM tip *



* P. Mesquida, PhD thesis, ETH Zurich, 2002

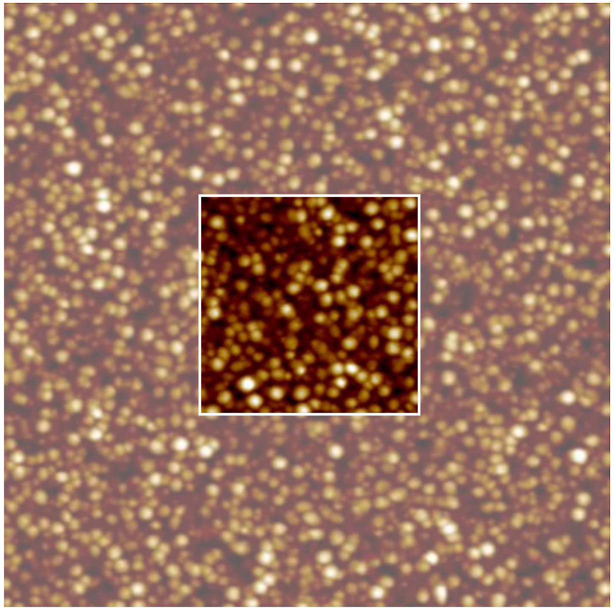
Summary and outlook

- electrical SPM techniques allow for unique and complementary information compared to conventional “macroscopic” results from MIS structures (even in ambient conditions!)
- direct quantification or correlation with results from conventional methods possible
- KPFM based procedure for nanoscale thickness mapping has been demonstrated
- future work
  - further development of cAFM for improved evaluation of current conduction mechanisms at the nanoscale
    → higher sensitivity (better amplifiers), shielded tips, T dependent measurements (heated chuck), modeling, …
  - improvement of thickness measurement method
    → in-situ charging or at least “in-tool” charging with very accurate stage

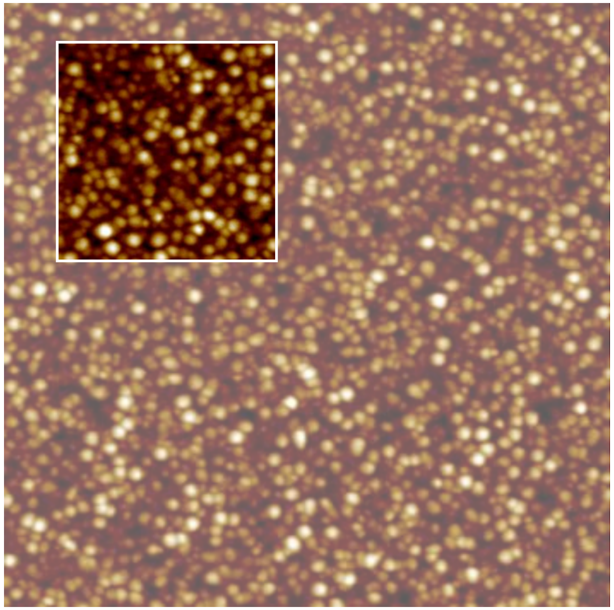
Nanoscale characterization of high-k dielectrics by electrical SPM methods

- **Limitations and solutions**
  - unique topography features allow unambiguous localization of position of interest

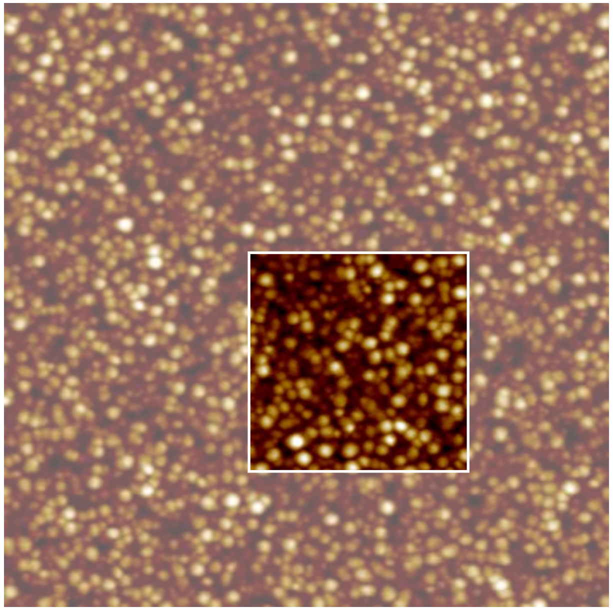
topography measurement A



topography measurement B



topography measurement C



  - sample positioning accuracy sufficient and evaluation procedure not required
  - corresponding KPFM data can be directly used to evaluate EOT