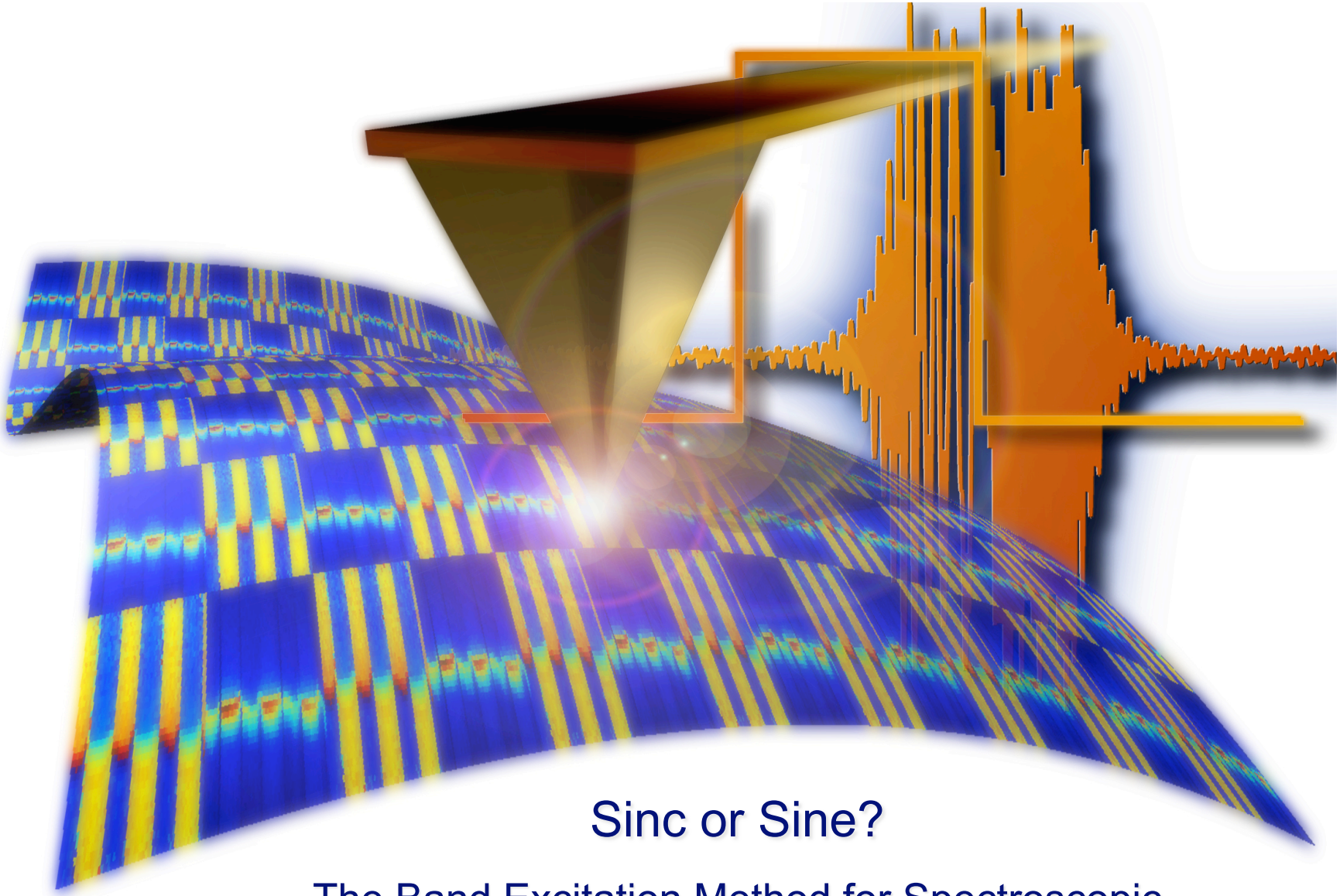
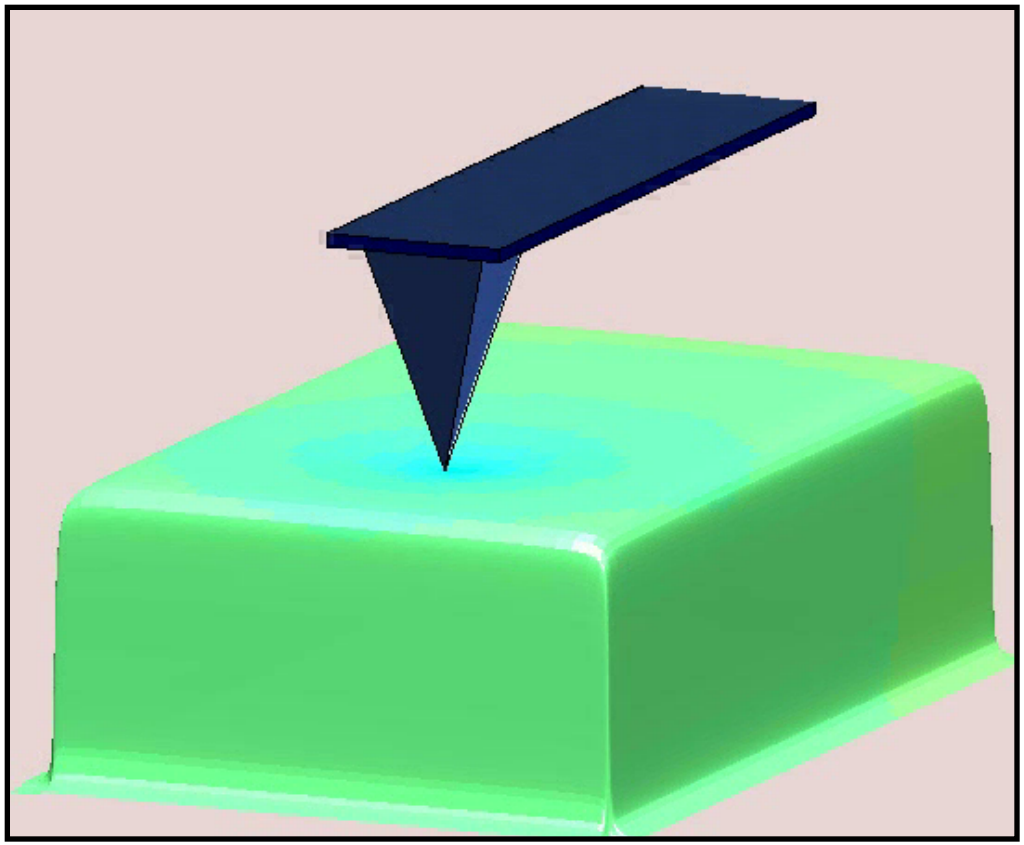


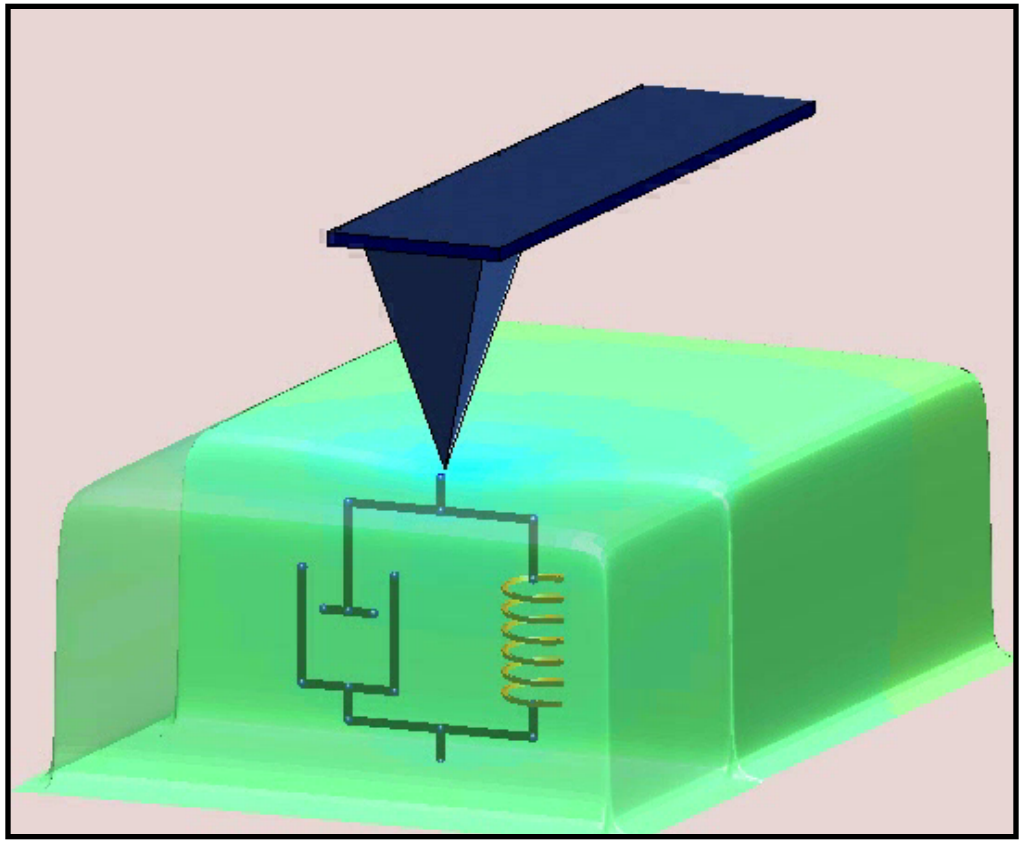
Sinc or Sine?

The Band Excitation Method for Spectroscopic Imaging in Scanning Probe Microscopy

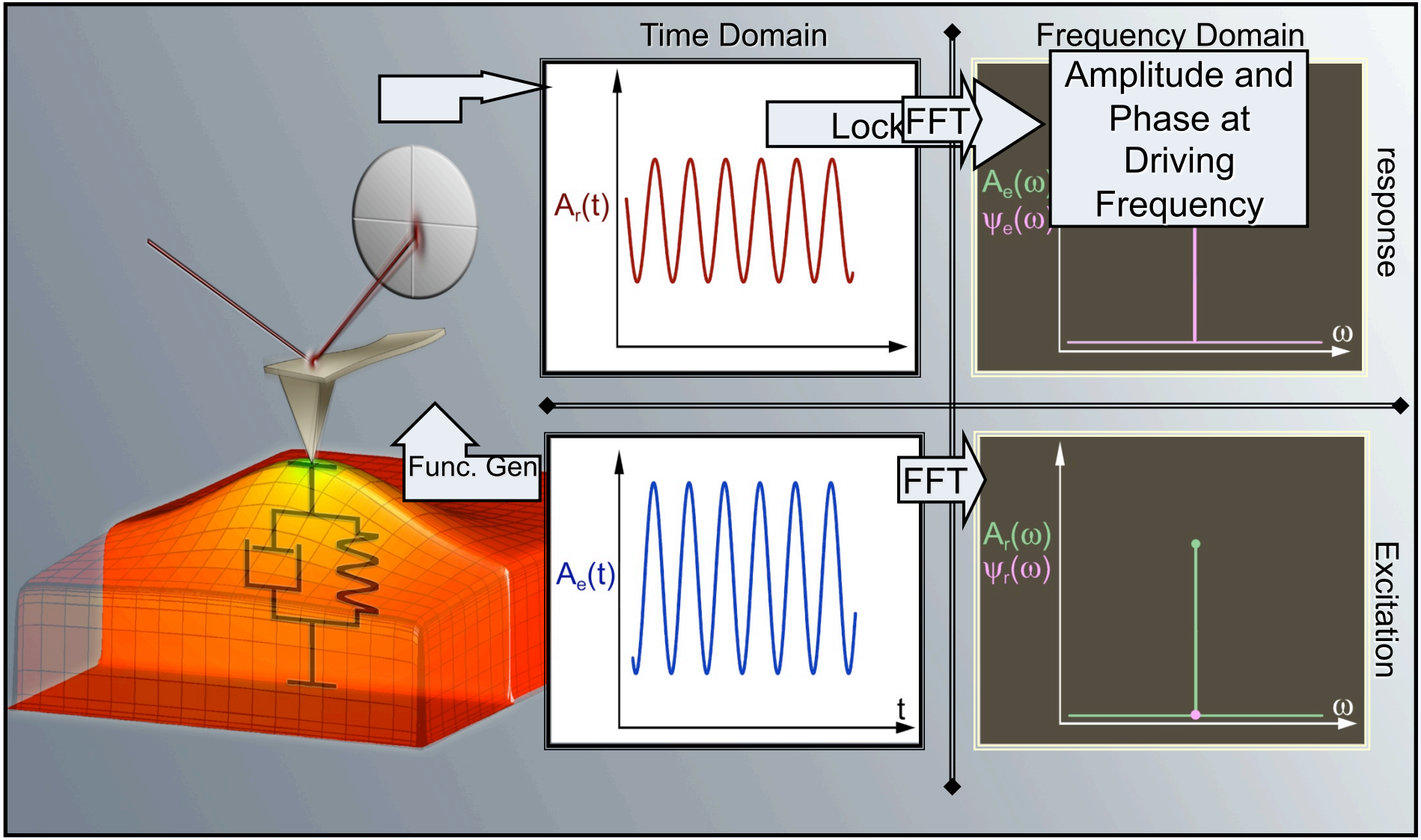
Stephen Jesse, M.P. Nikiforov, P. Maksymovych, S.V. Kalinin

- Motivation
- Constructing the BE waveform
- Examples
  - Piezo-response force microscopy/spectroscopy
  - Nano-thermal analysis
  - Magnetic force microscopy
  - Nonlinear tip-surface interactions
- Principal Component Analysis

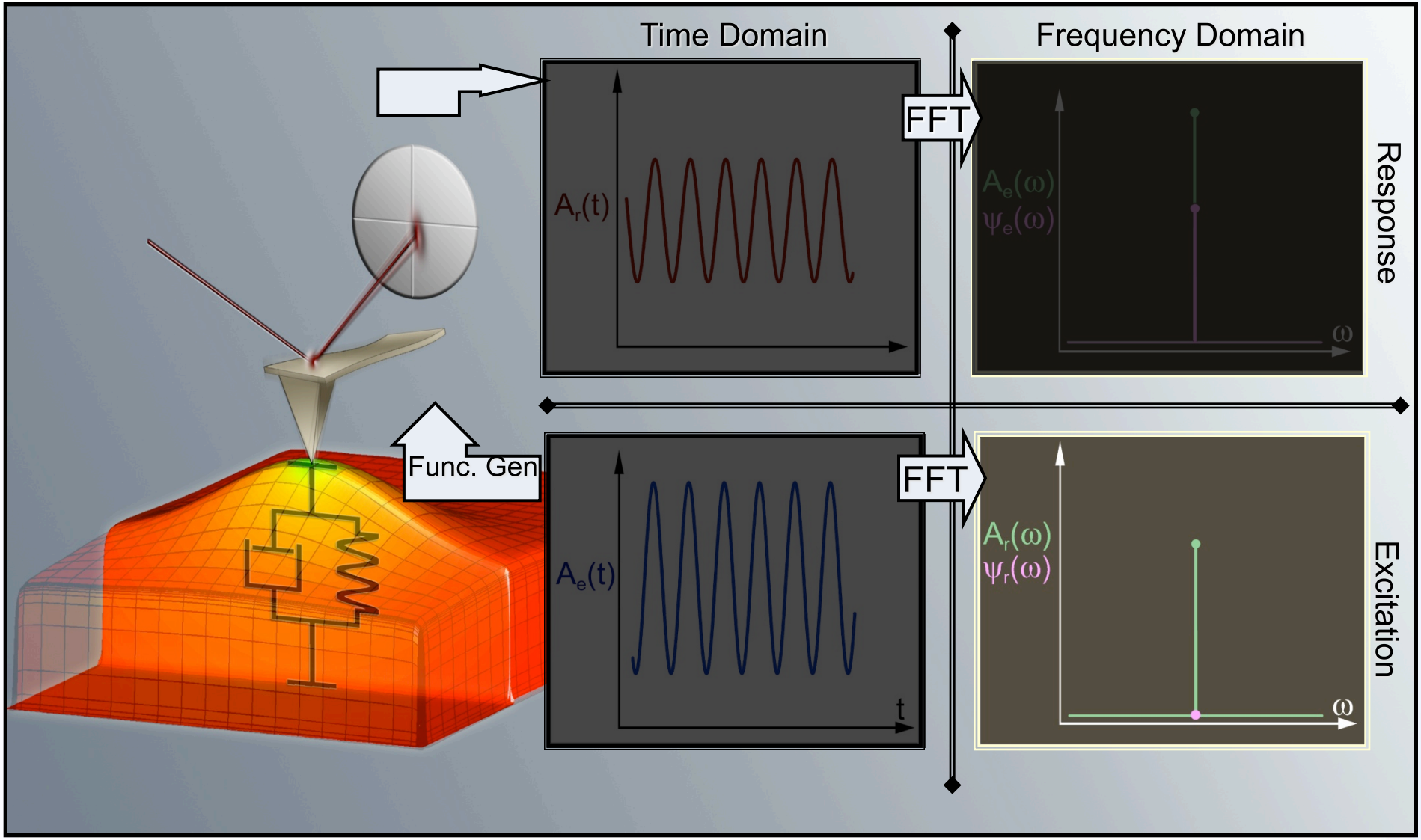




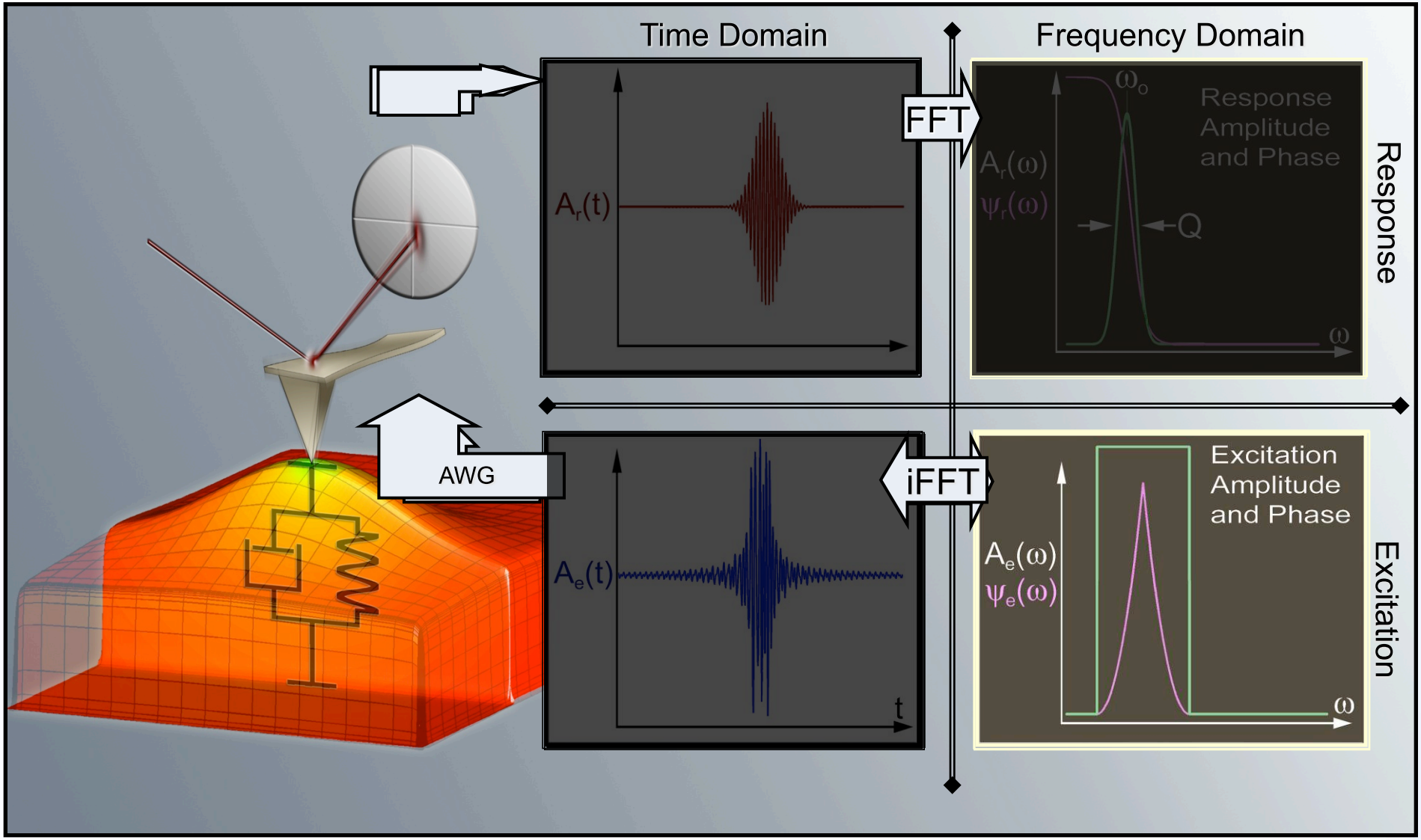
spm methods to date



spm methods to date



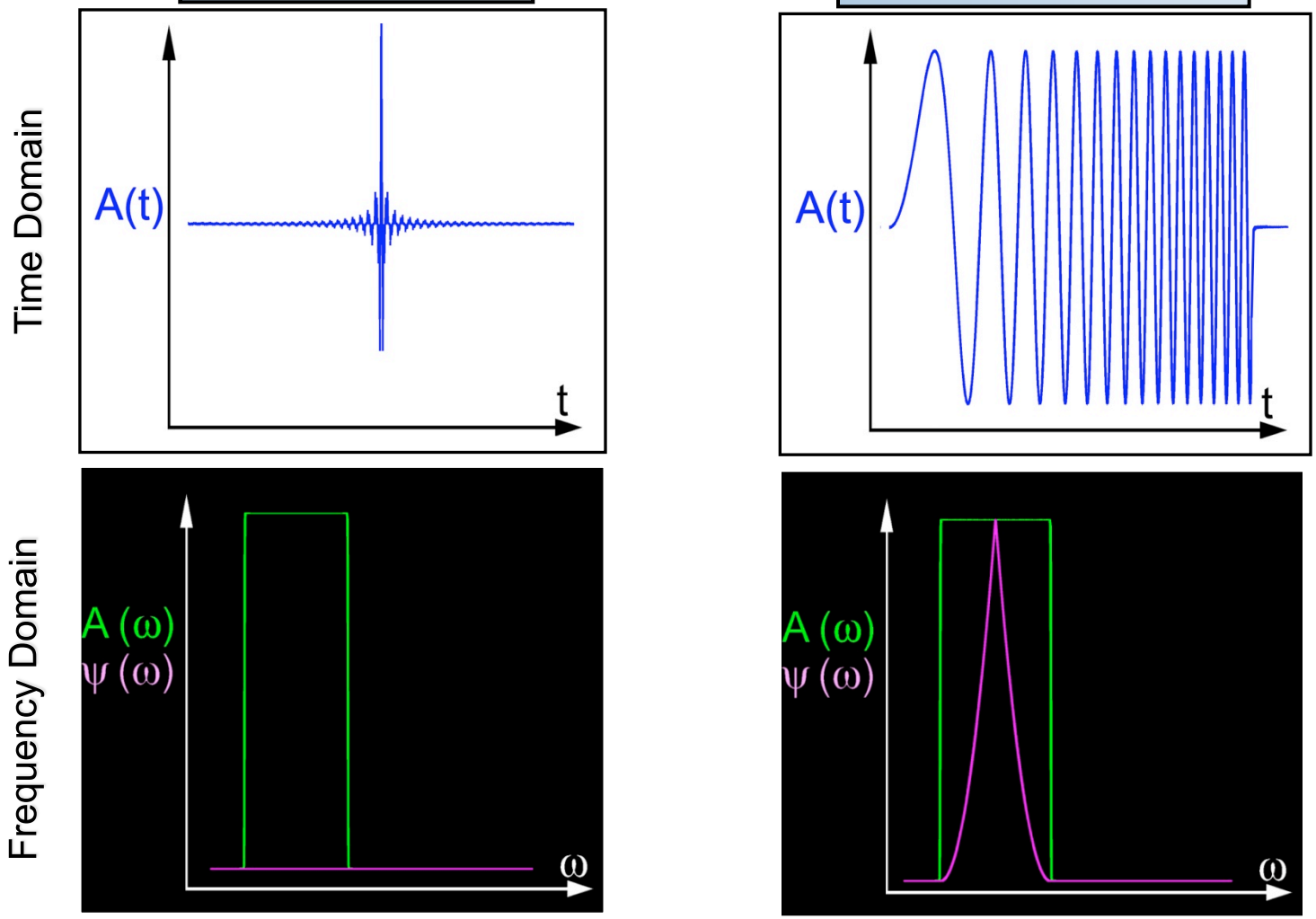
the band excitation method



to ϕ or not to ϕ : the role of phase

$$SINC = \frac{\sin(a \cdot t)}{t}$$

$$CHIRP = \sin\left(\frac{a \cdot t^2}{2}\right)$$



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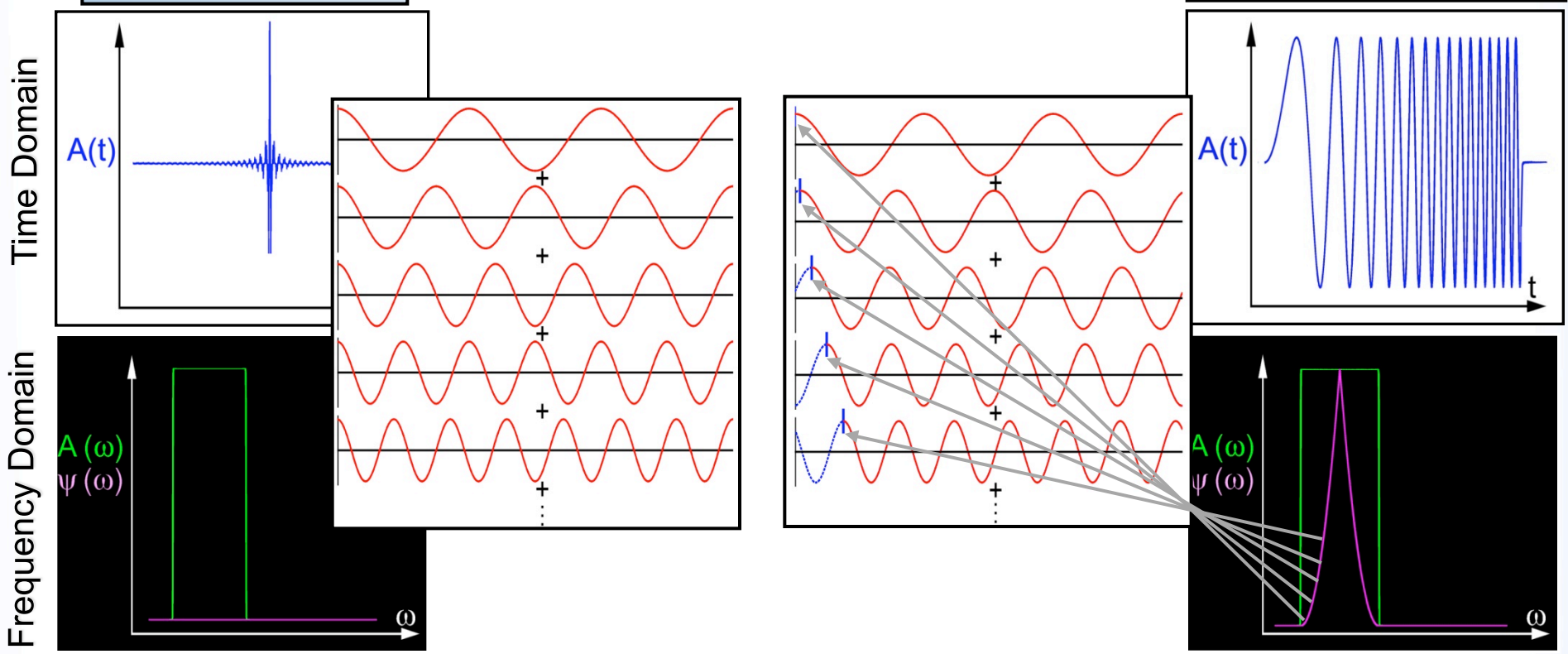

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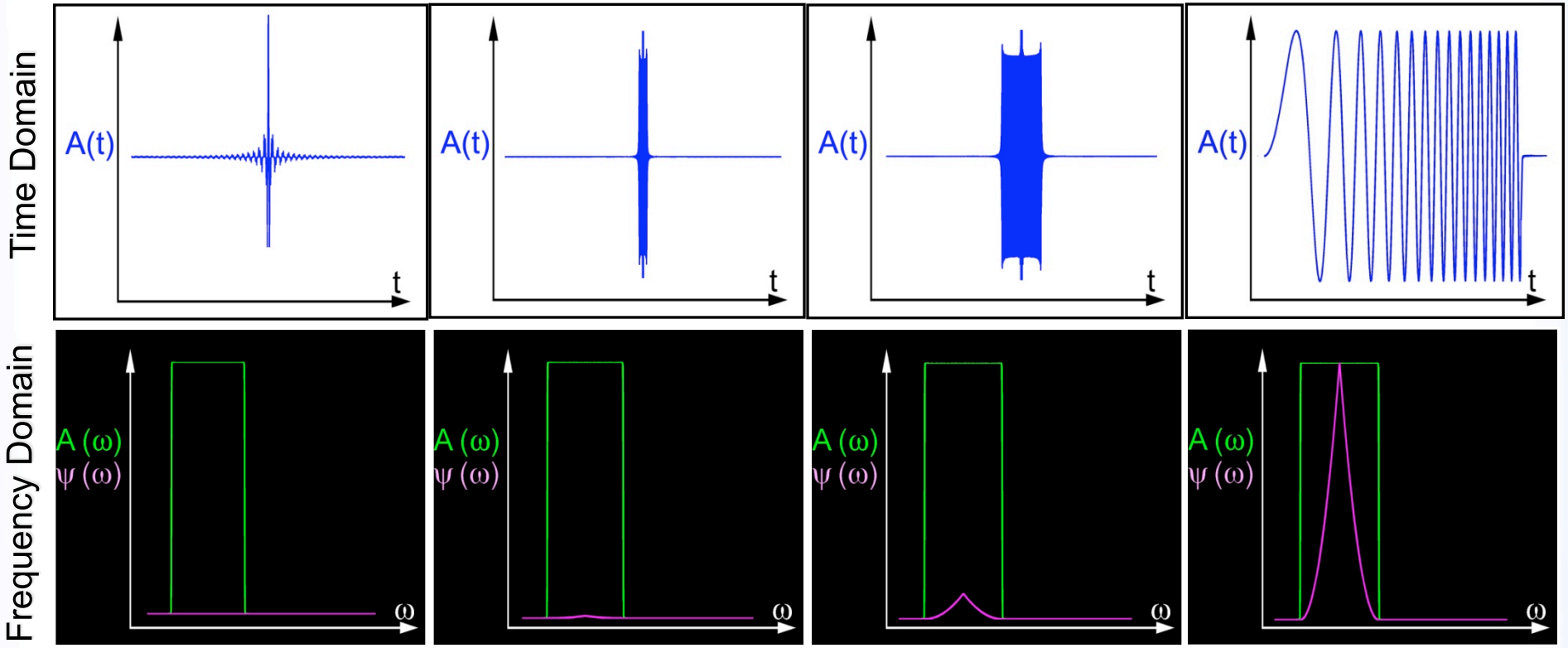


truncating the waveform: frequency resolution vs. signal-to-noise

← dwell time per pixel →

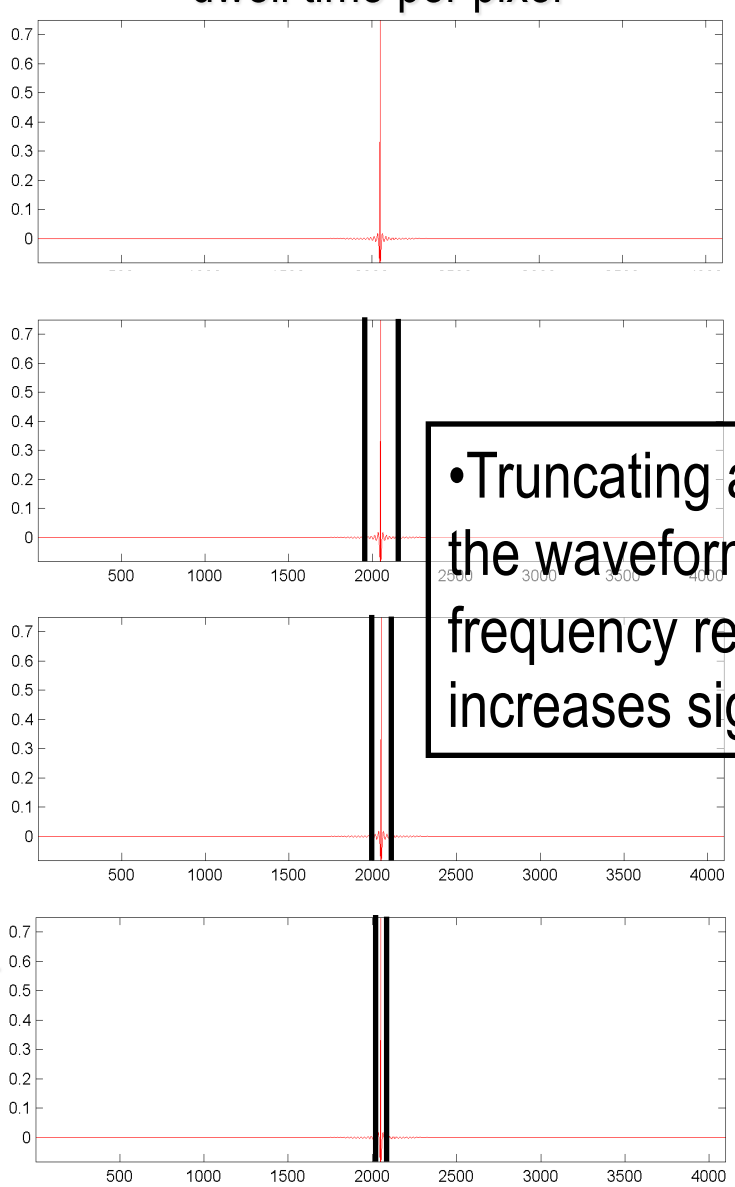
measured response

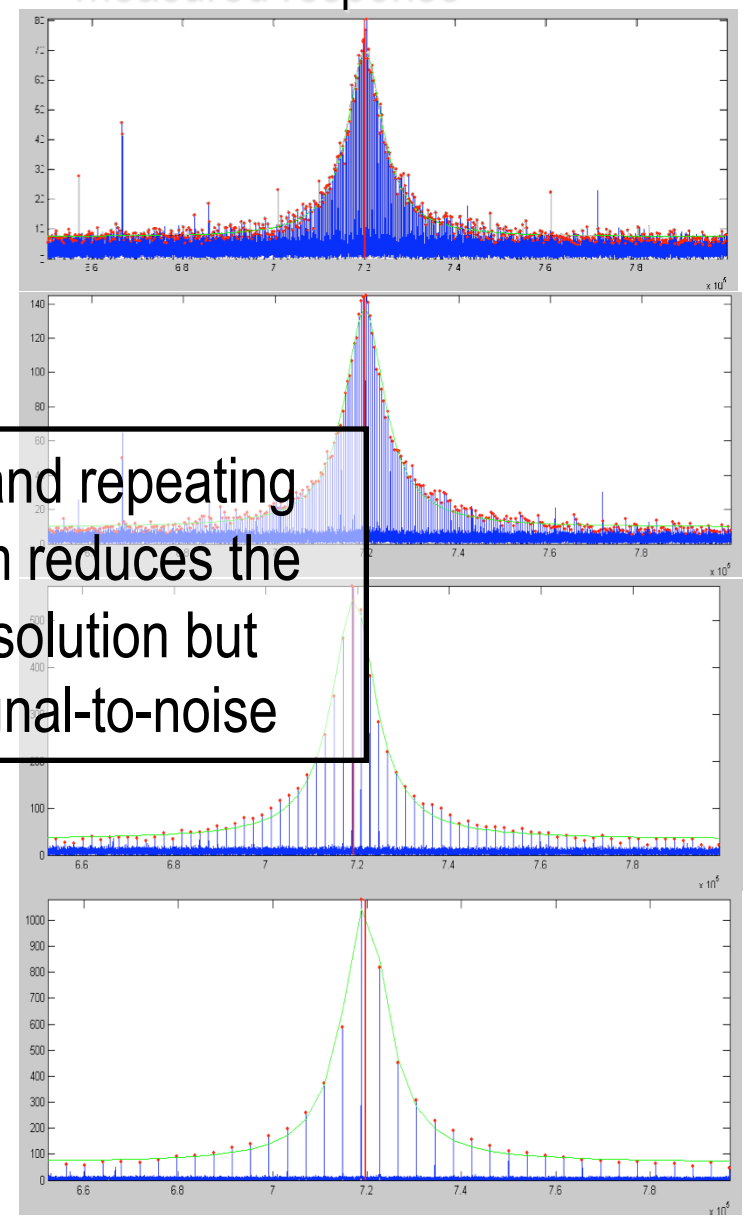
Truncate to 1/8
Repeat 8 times

Truncate to 1/16
Repeat 16 times

Truncate to 1/32
Repeat 32 times

Truncate by 1/64
Repeat 64 times



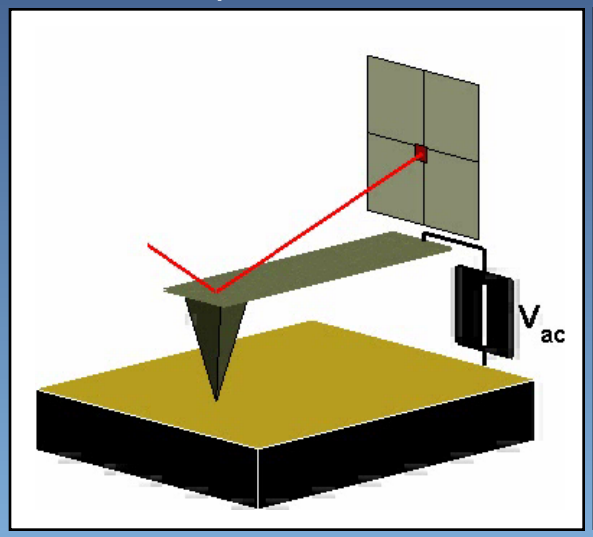


- Truncating and repeating the waveform reduces the frequency resolution but increases signal-to-noise

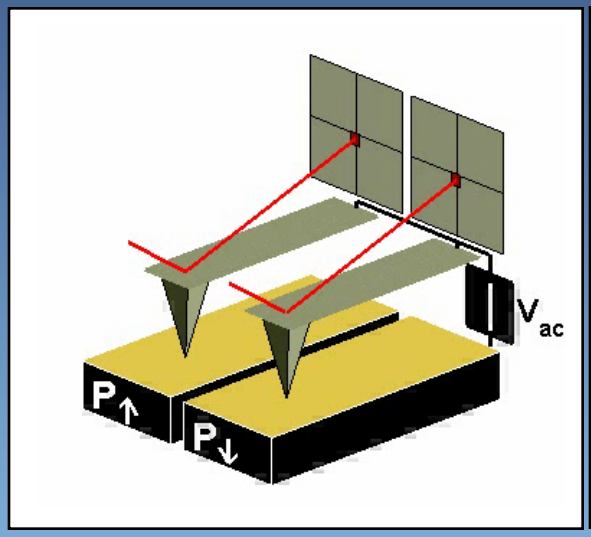
piezo-response force microscopy (PFM)

piezo-response force microscopy - pfm

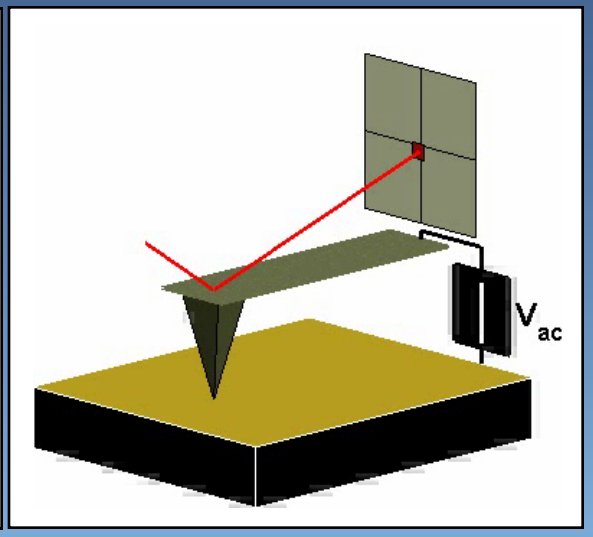
Amplitude: VPFM

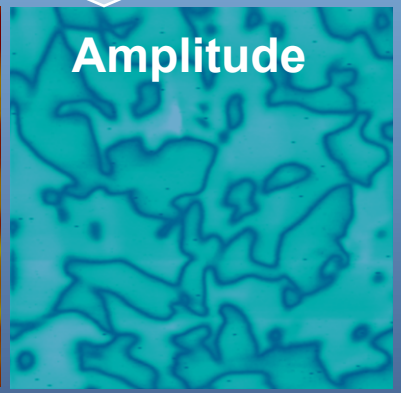


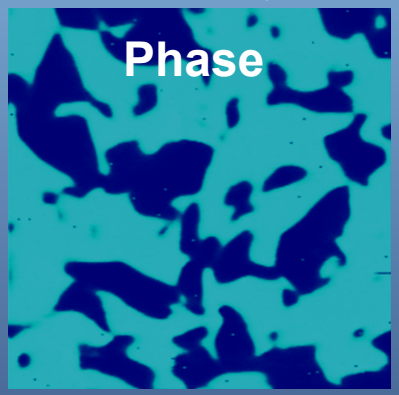
Phase



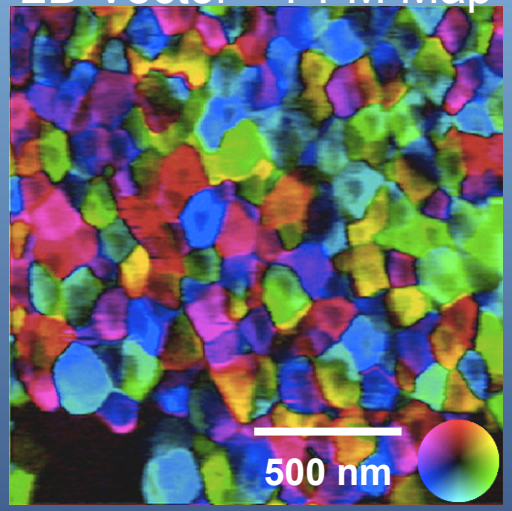
Vector-PFM



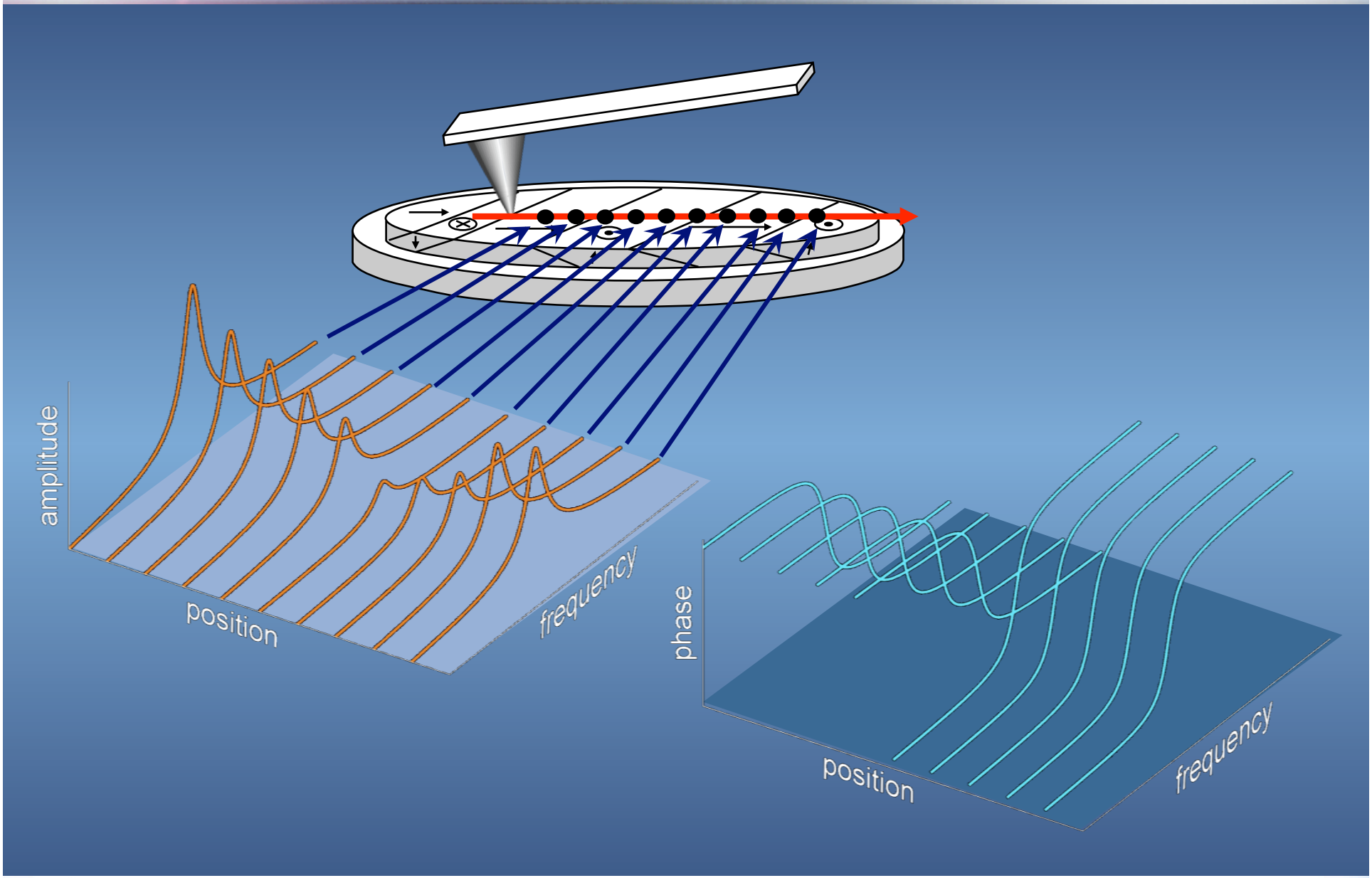




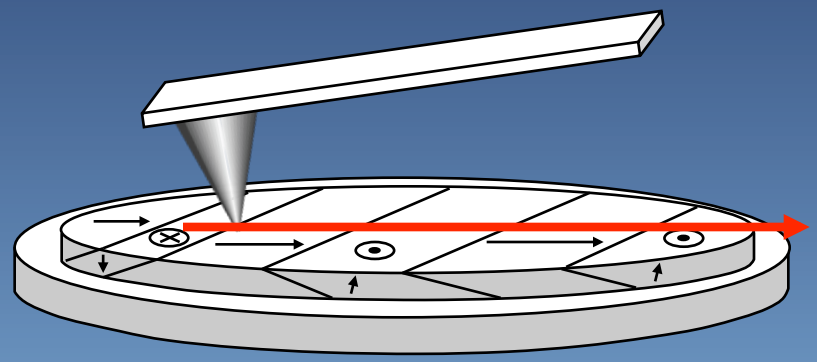
2D Vector – PFM Map

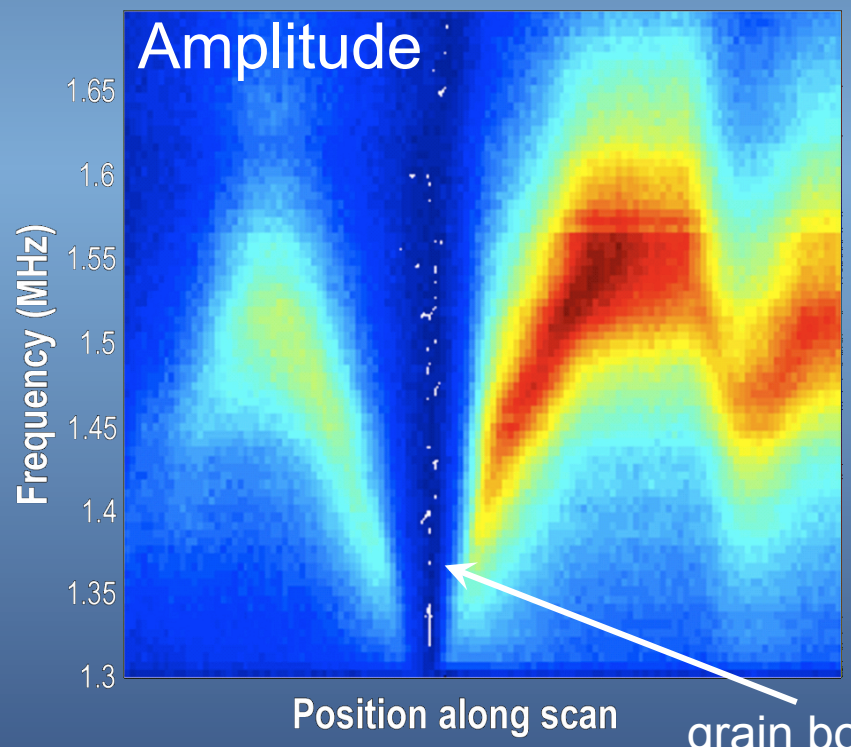


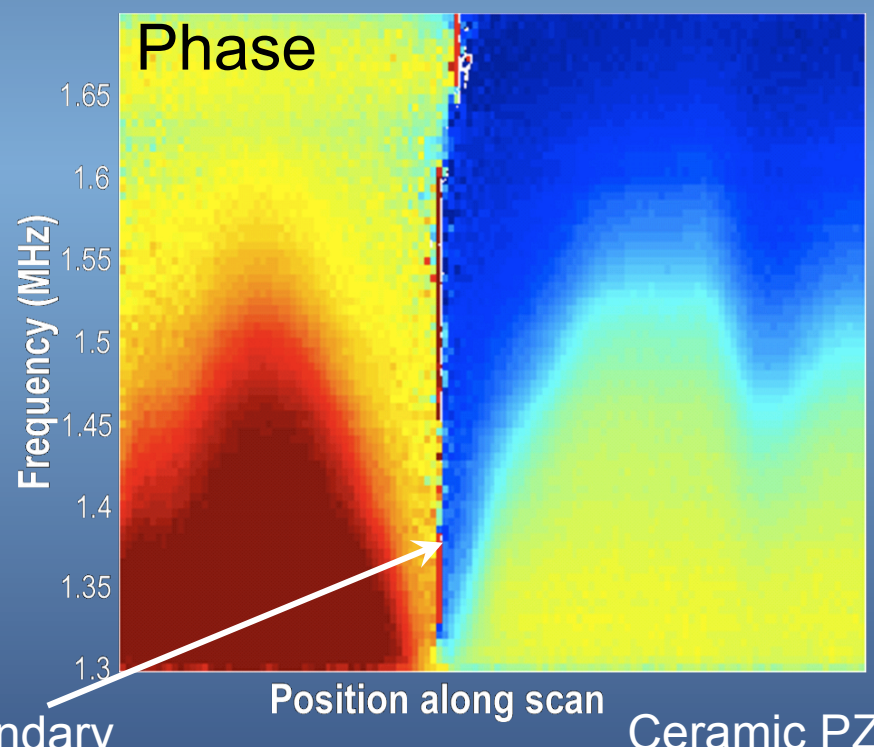
Band Excitation - PFM



Band Excitation - PFM



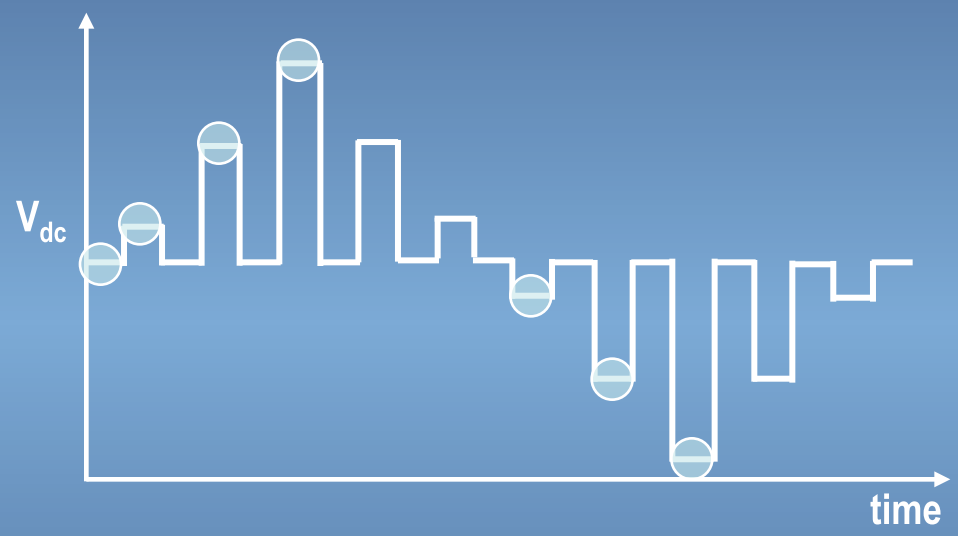


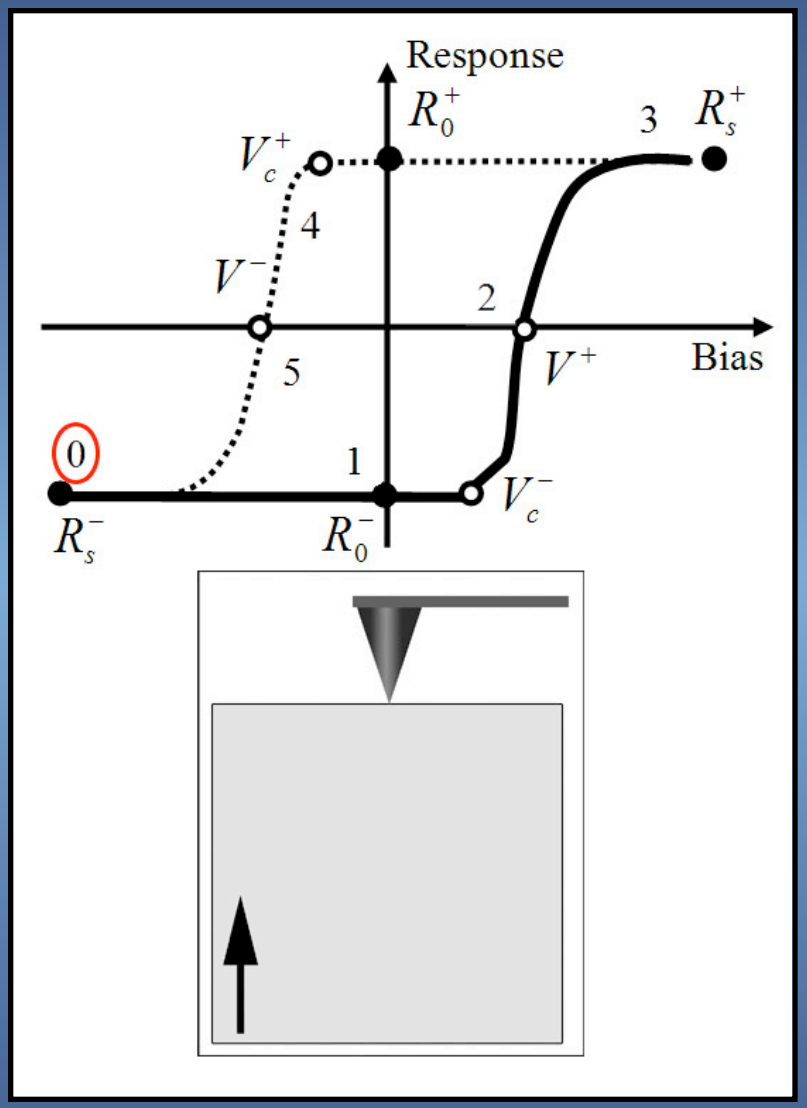


grain boundary

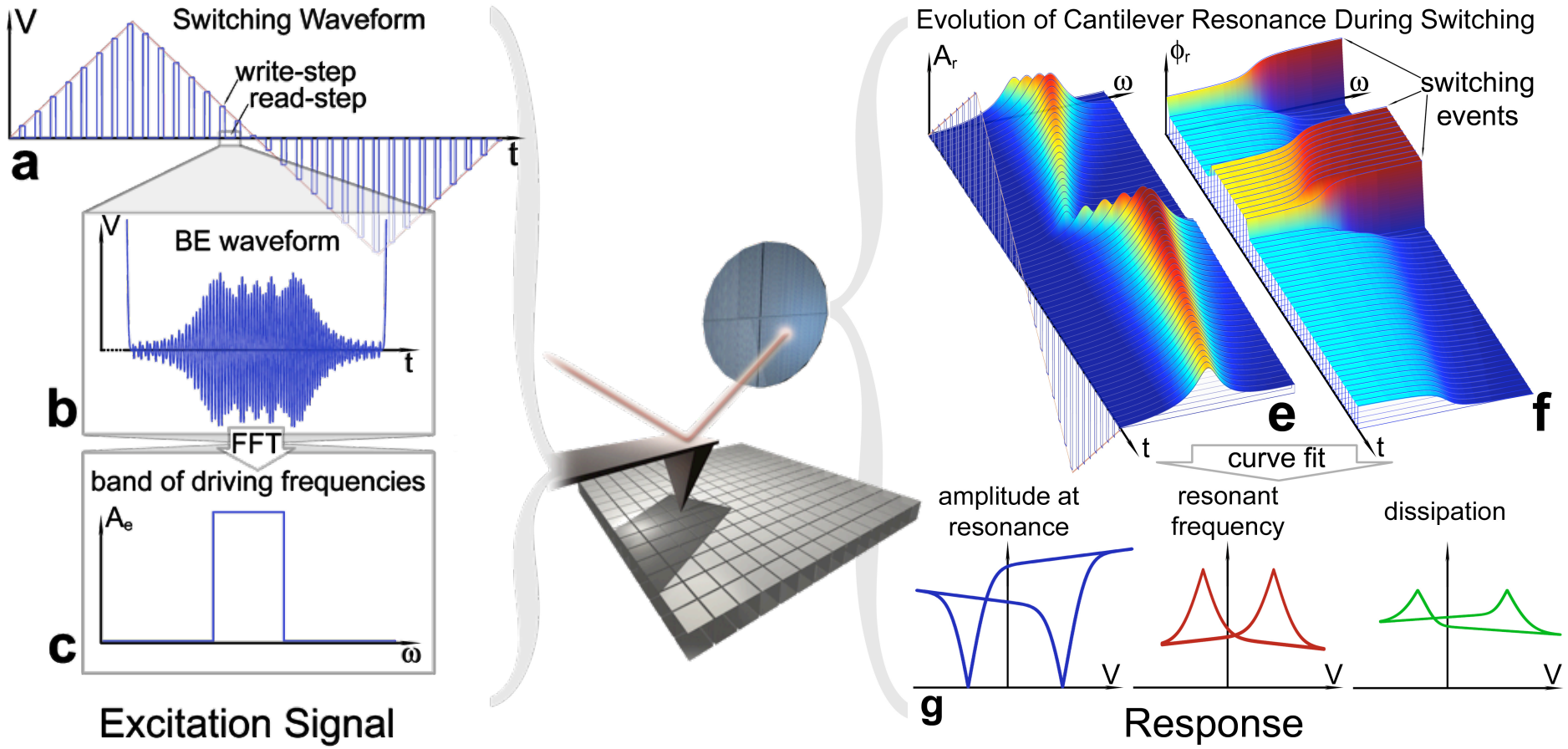
Ceramic PZT

switching spectroscopy piezo-response force microscopy

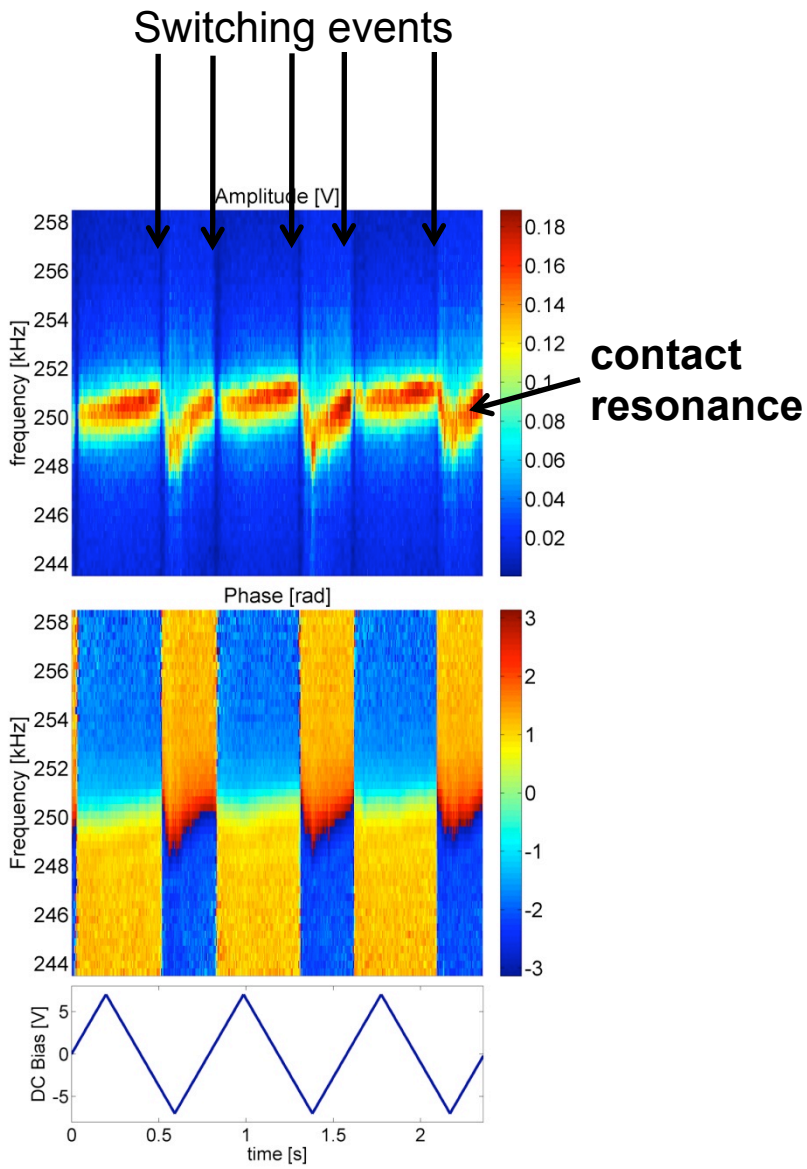




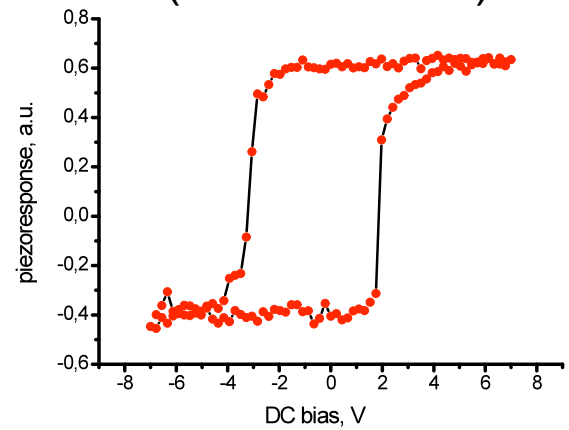
band excitation + switching spectroscopy



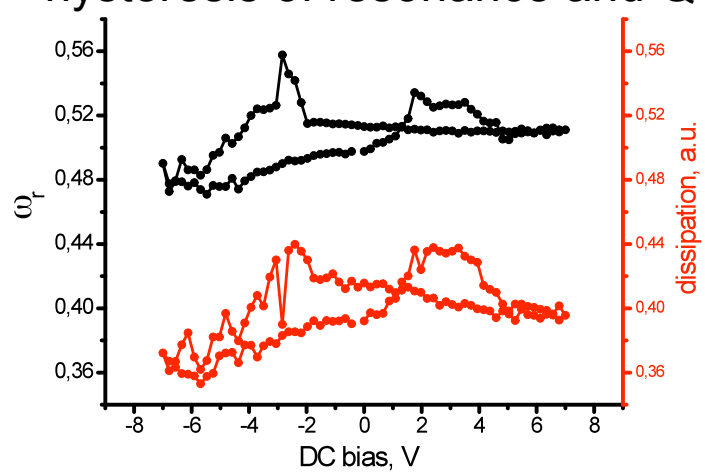
band excitation + switching spectroscopy



amplitude hysteresis loop (on-resonance)



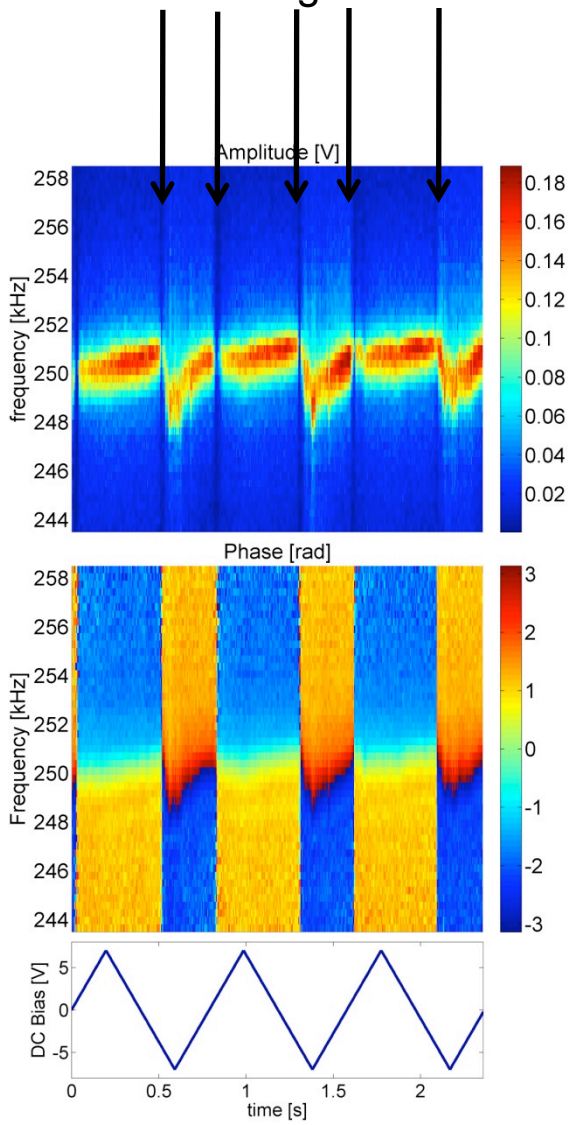
hysteresis of resonance and Q



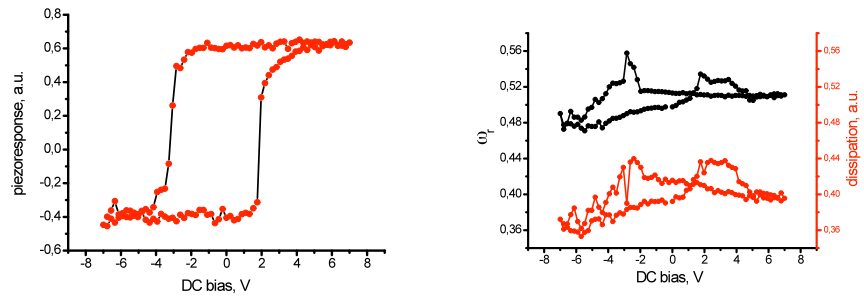
S. Jesse, P. Maksymovych, and S. V. Kalinin, *Rapid Multidimensional Data Acquisition in Scanning Probe Microscopy Applied to Local Polarization Dynamics and Voltage Dependent Contact Mechanics*, Appl. Phys. Lett., in print

band excitation + switching spectroscopy

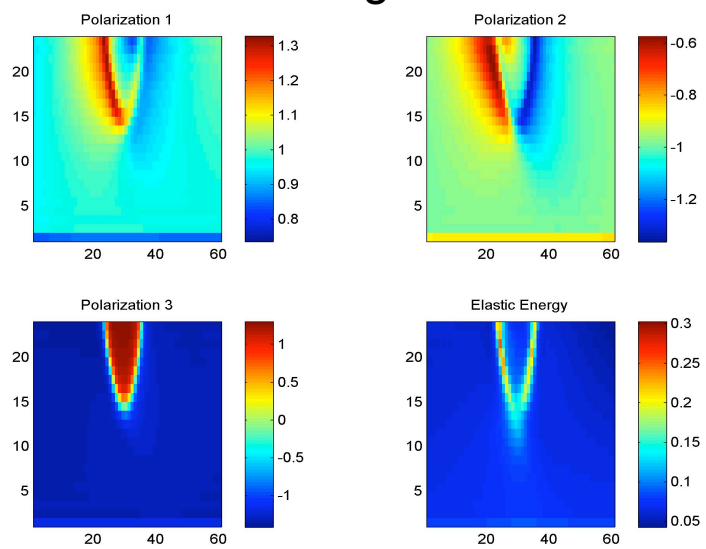
Switching events



Hysteresis loops obtained from PFS data

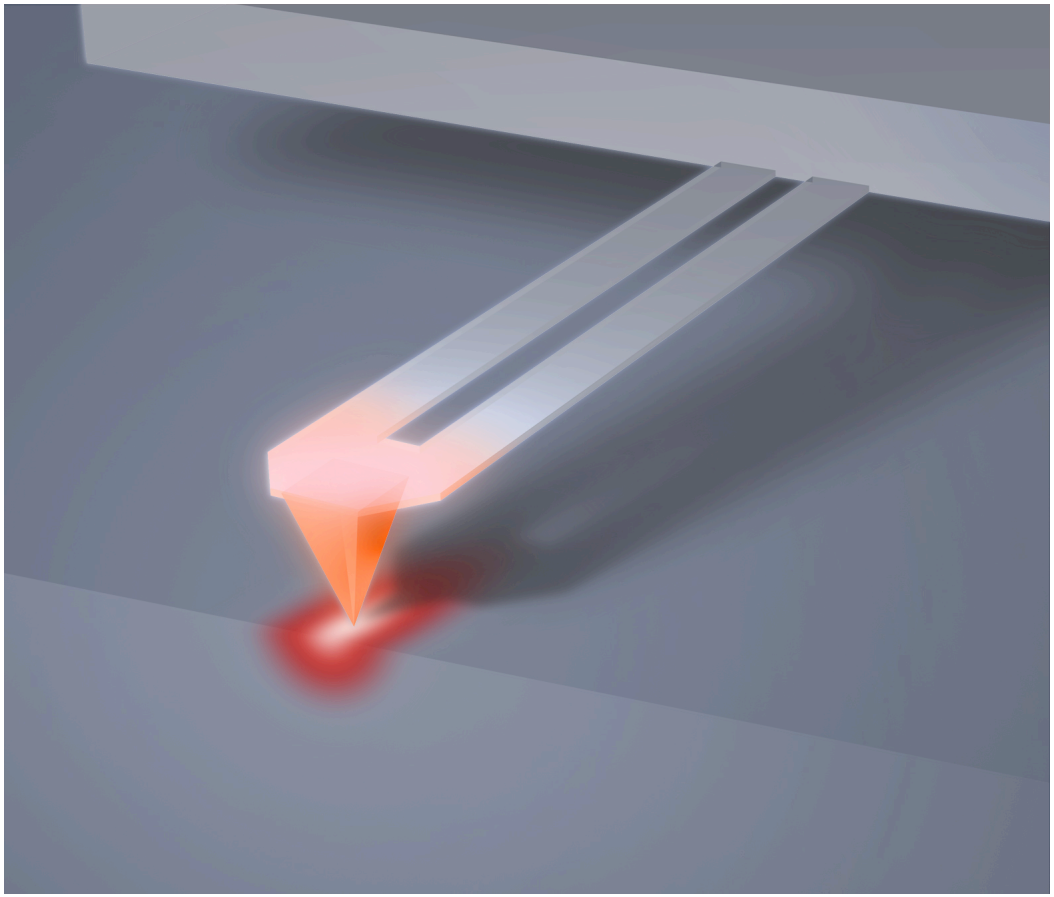


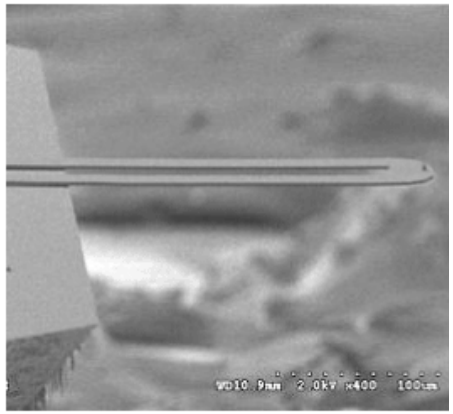
phase field modeling of the nucleating domain



Nanoscale Thermal Analysis
(nano-TA)

nano-thermal analysis



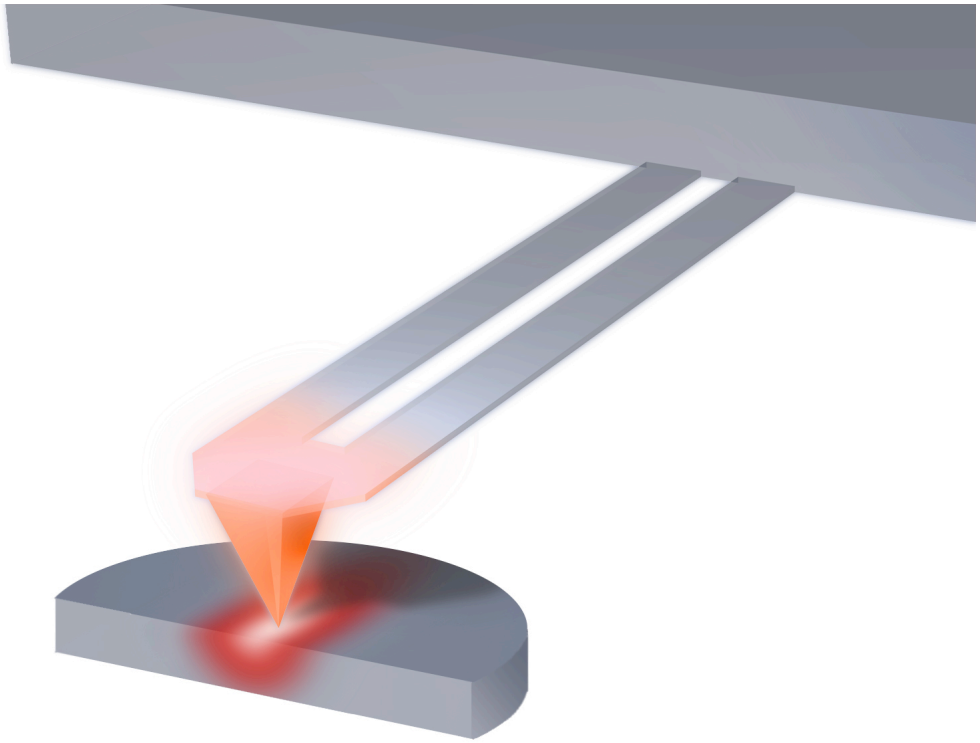


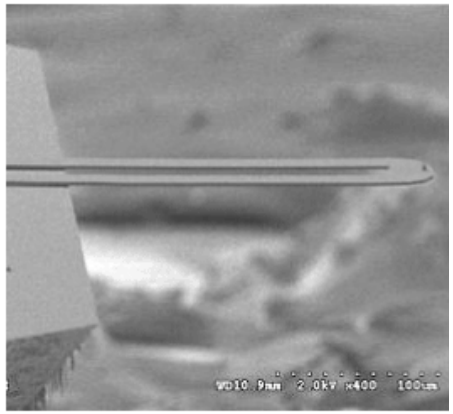
Anasys Thermal Probe

In traditional nano-TA

- Tip is brought into contact
- Current is applied, tip heats
- Cantilever deflection indicates the onset of melting

nano-thermal analysis





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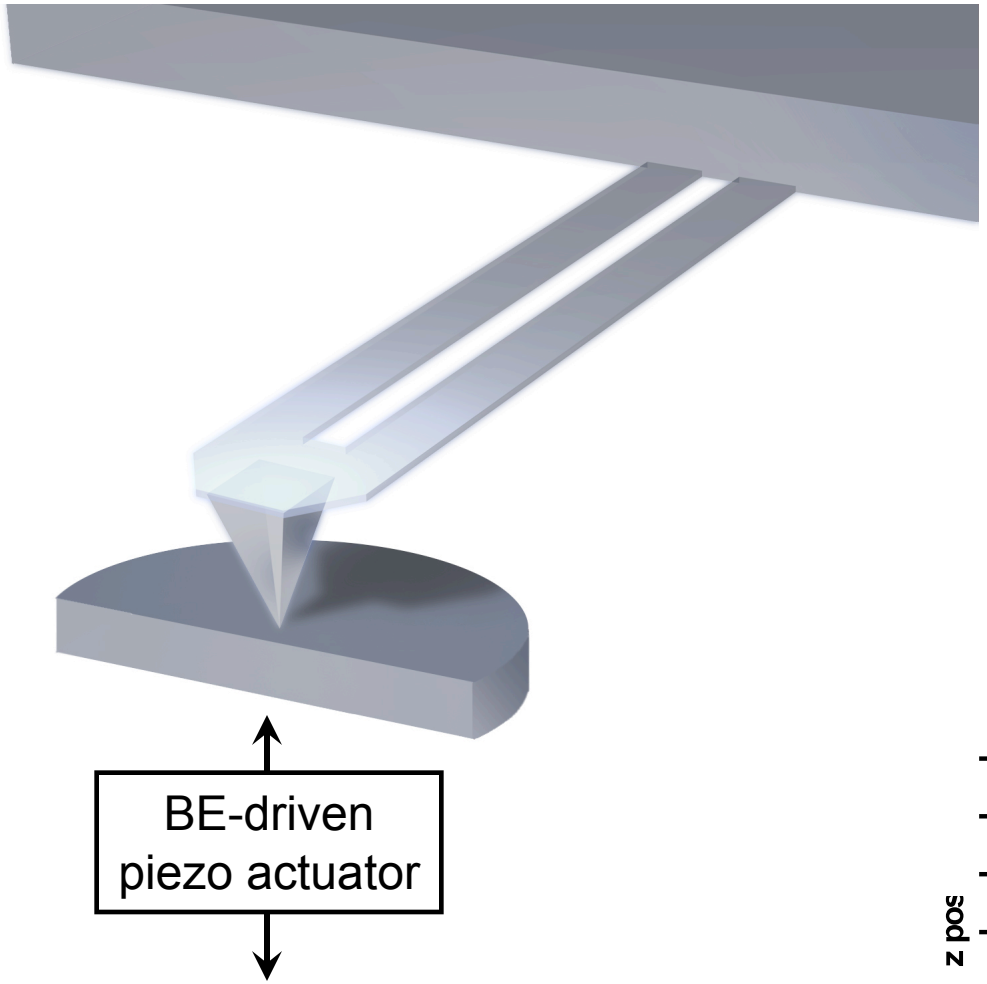
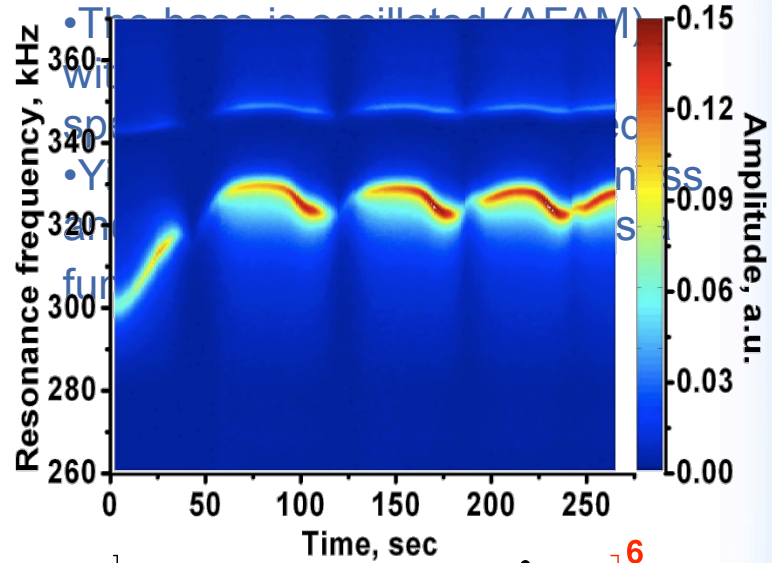
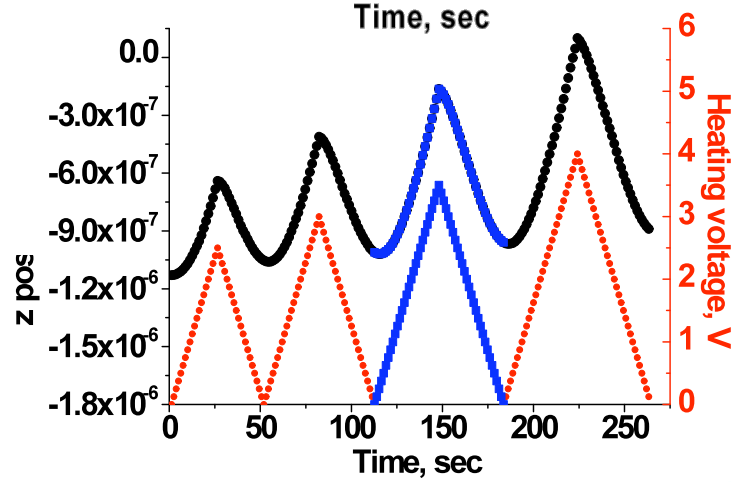
nano-thermal analysis



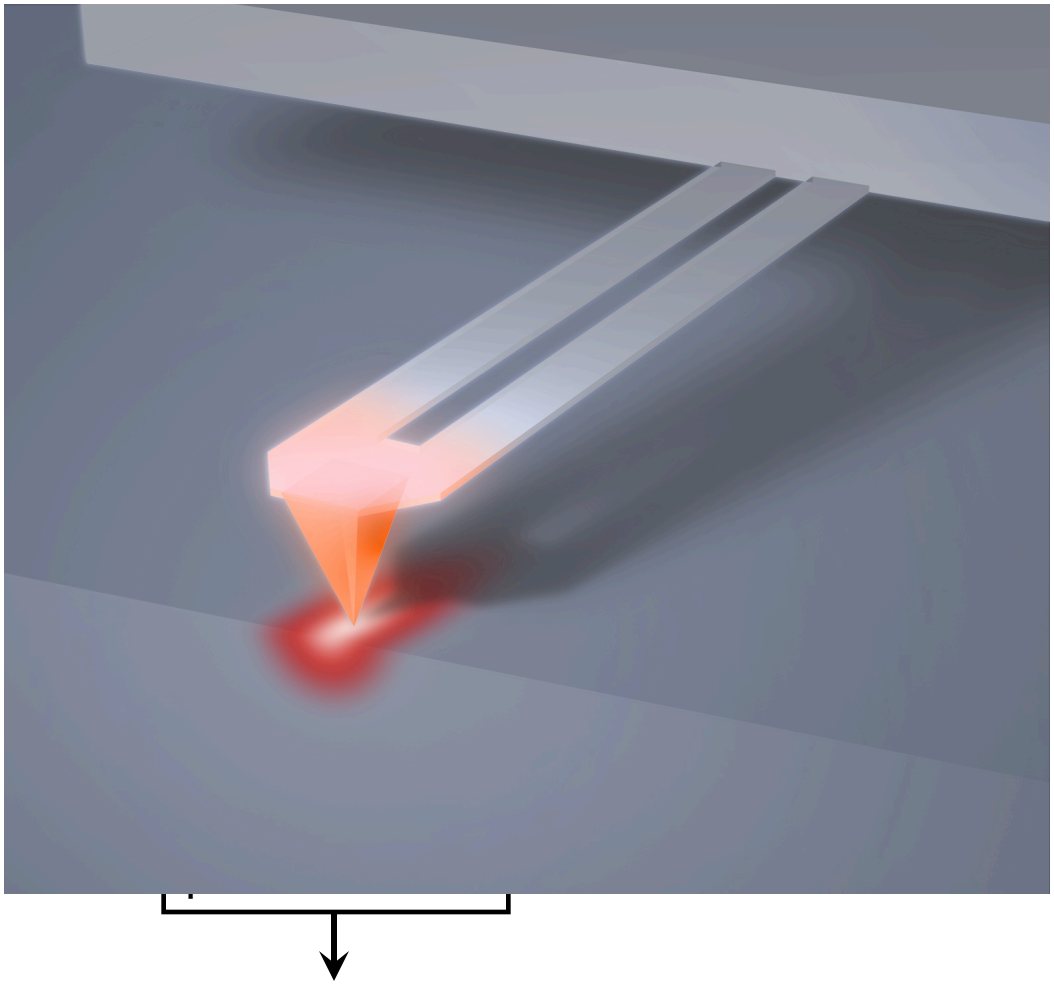
In BE nano-TA (version 1)

- Tip is brought into contact
- Current is applied, tip heats
- The base is oscillated (AFAM) with spec
- Y
and
fun





nano-thermal analysis

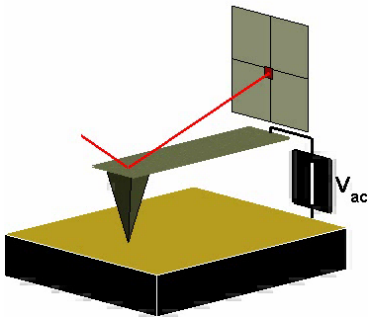


In BE nano-TA (version 1)

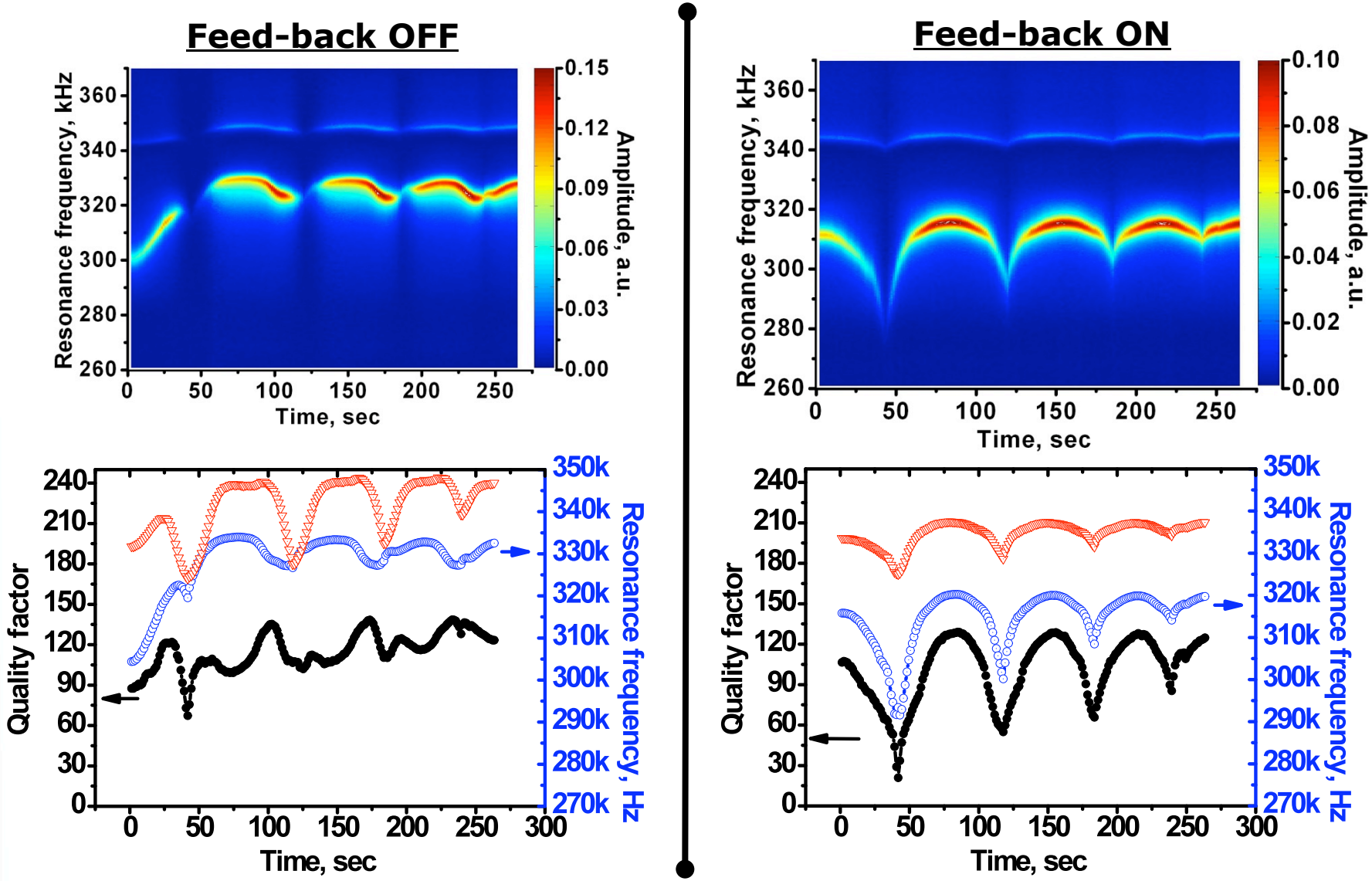
- Tip is brought into contact
- Current is applied, tip heats
- The base is oscillated (AFAM) with a BE waveform, and the spectral response is measured
- Yielding, local change in stiffness and visco-elastic properties as a function of temperature

In BE nano-TA (version 2)

- Tip is brought into contact
- Current is applied, tip heats
- The BE waveform is sent as current through the cantilever itself

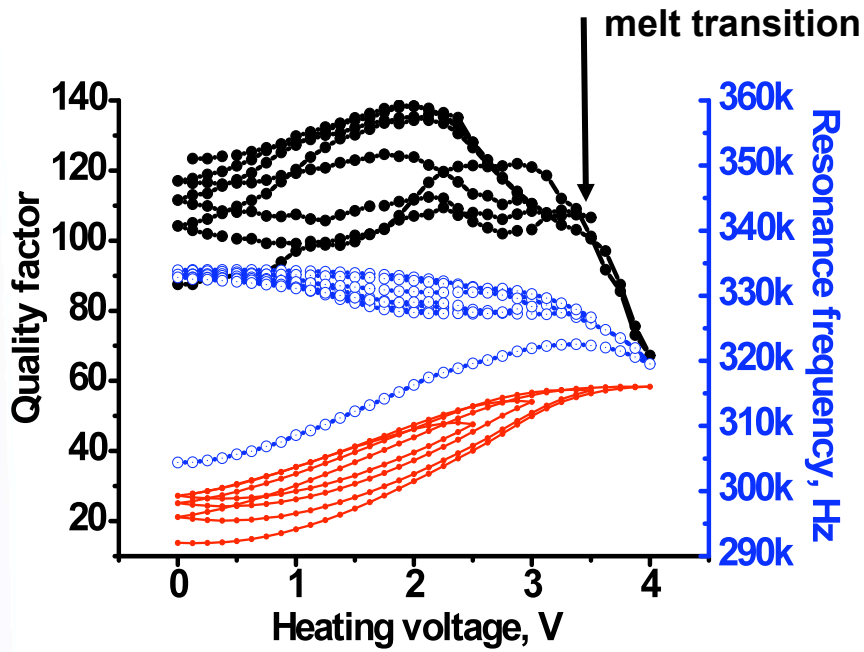


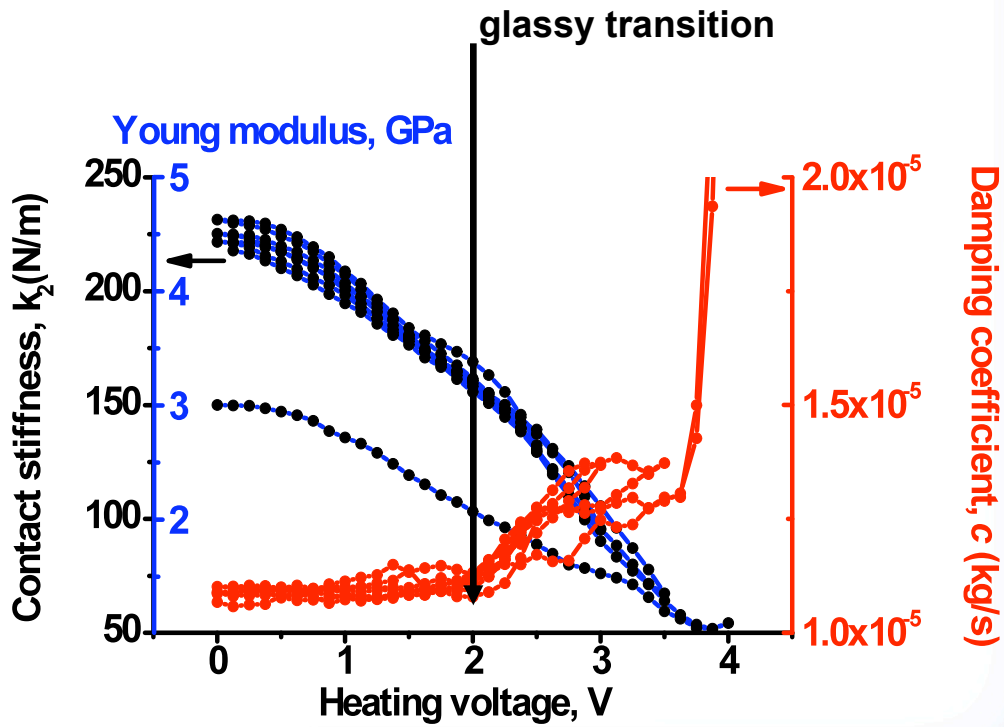
nano-thermal analysis



S. Jesse, M. Nikiforov, L. Germinario, and S. V. Kalinin, *Local Thermomechanical Characterization of Phase Transitions in Polymers using Band Excitation Atomic Force Acoustic Microscopy with Heated Probe*, Appl. Phys. Lett. **93**, 073104 (2008).

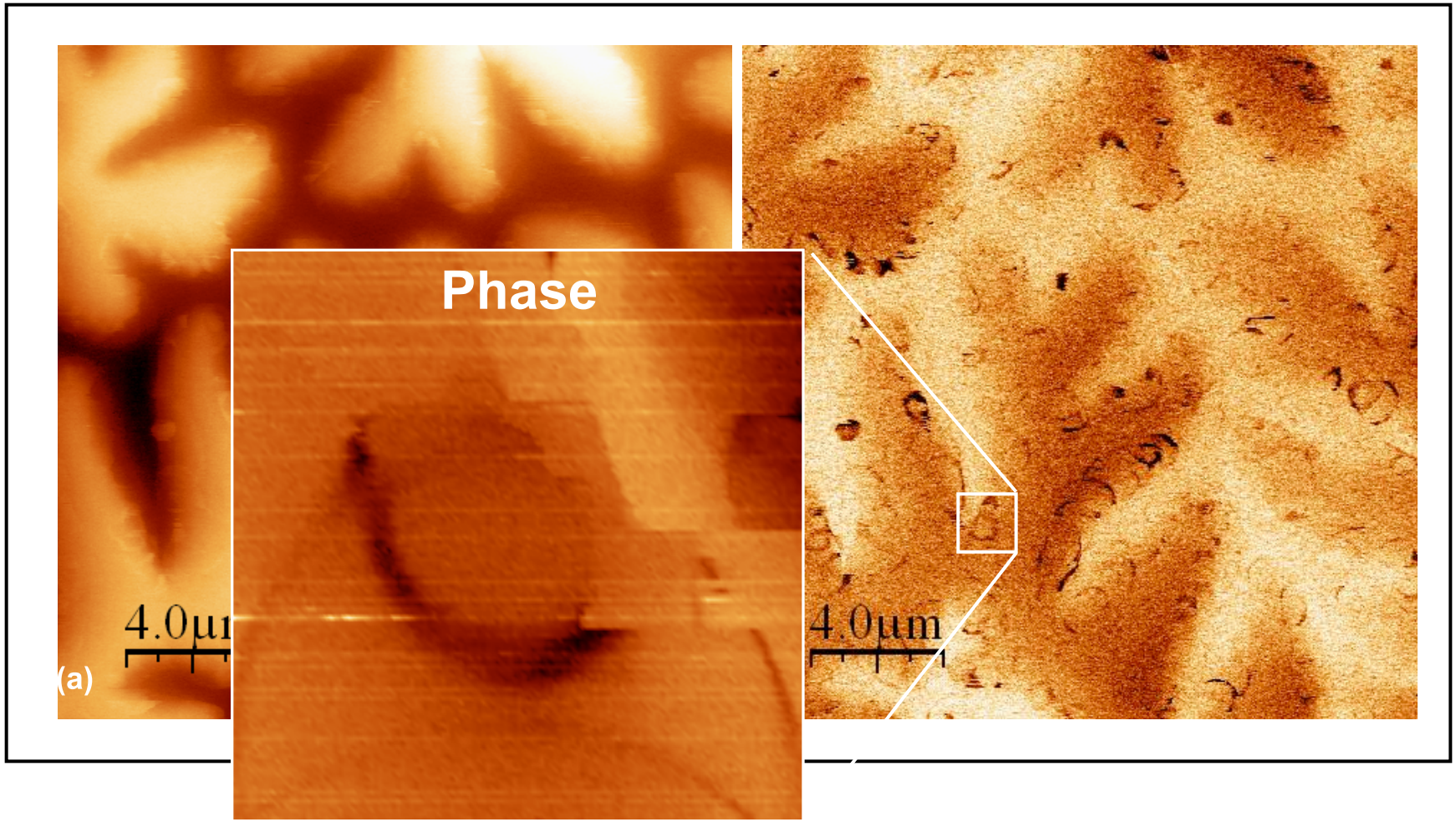
nano-thermal analysis





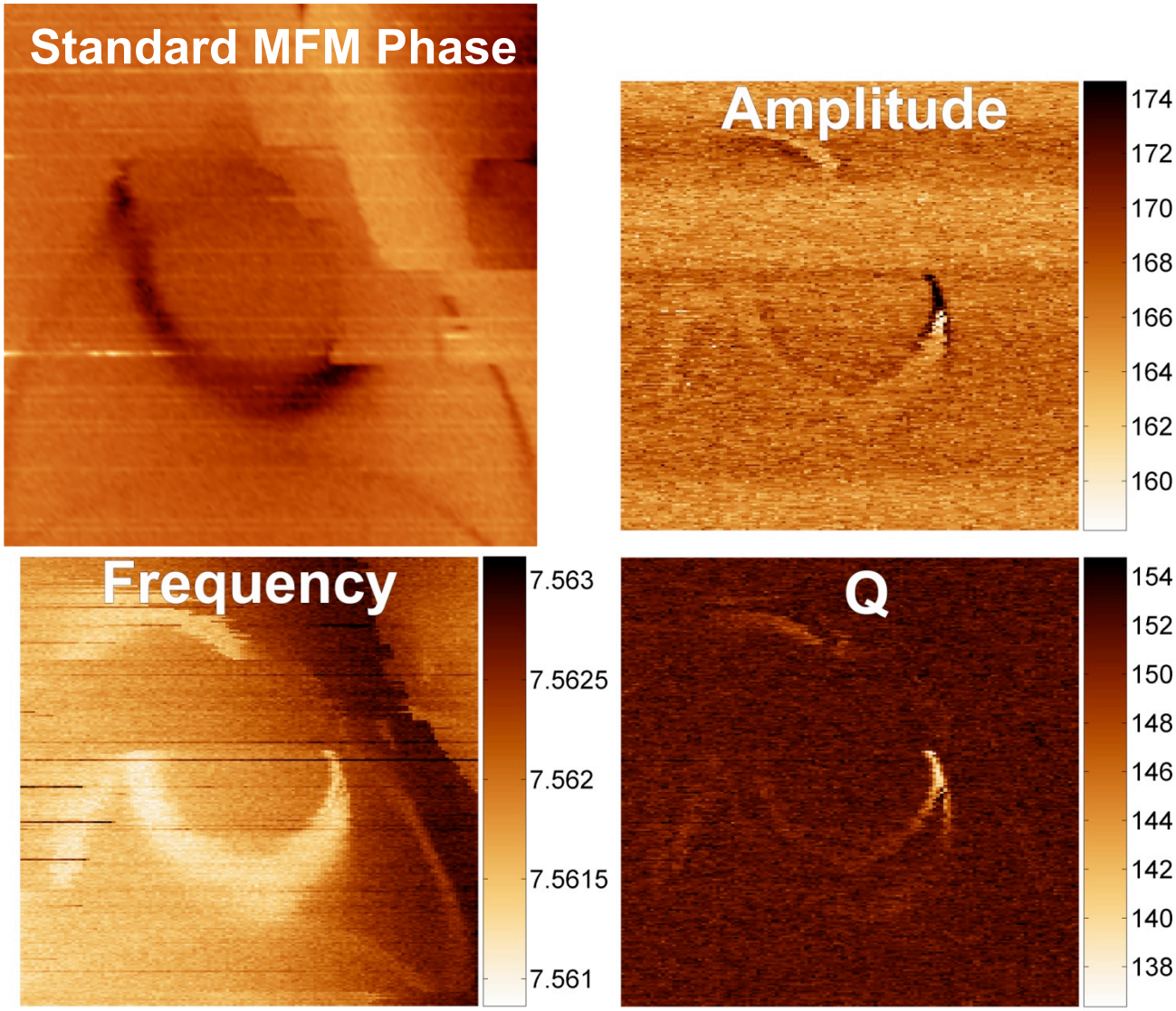
Magnetic Force Microscopy (MFM)

magnetic force microscopy



Single crystal Yttrium-Iron Garnet

magnetic force microscopy

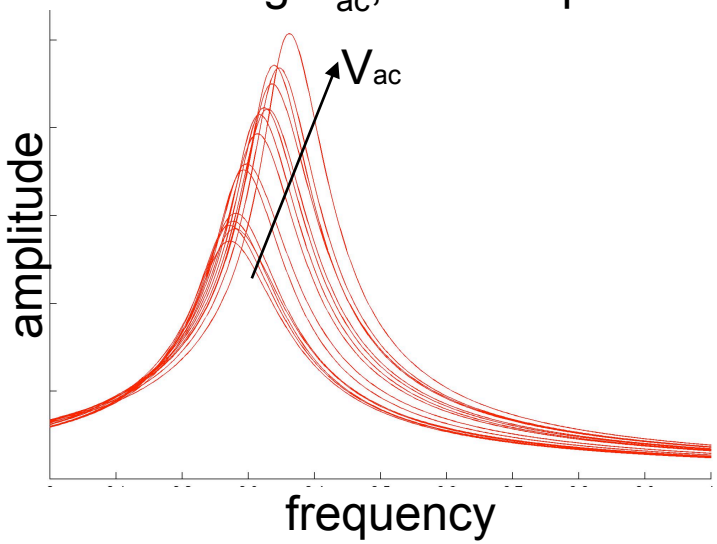


S. Jesse, S.V. Kalinin, R. Proksch, et. Al., *The Band Excitation Method for rapid mapping of energy dissipation on the nanoscale.* Nanotechnology. **18**, 435505 (2007).

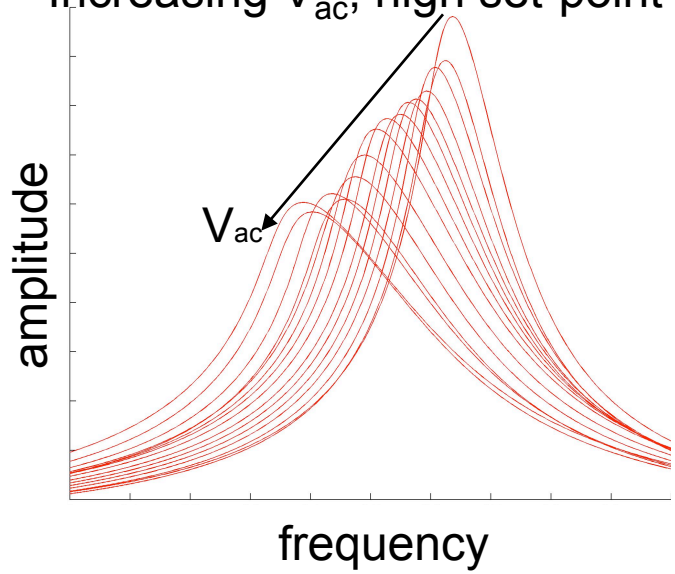
A window into non-linearities

non-linear responses, a look into contact mechanics

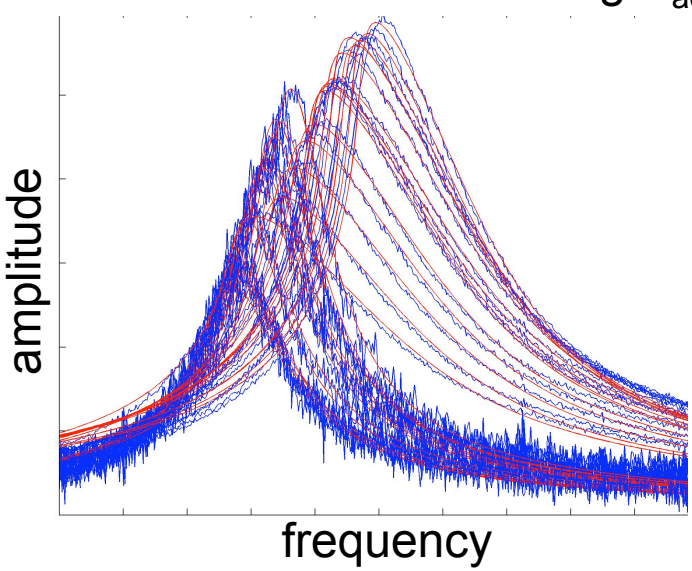
Increasing V_{ac}, low set-point

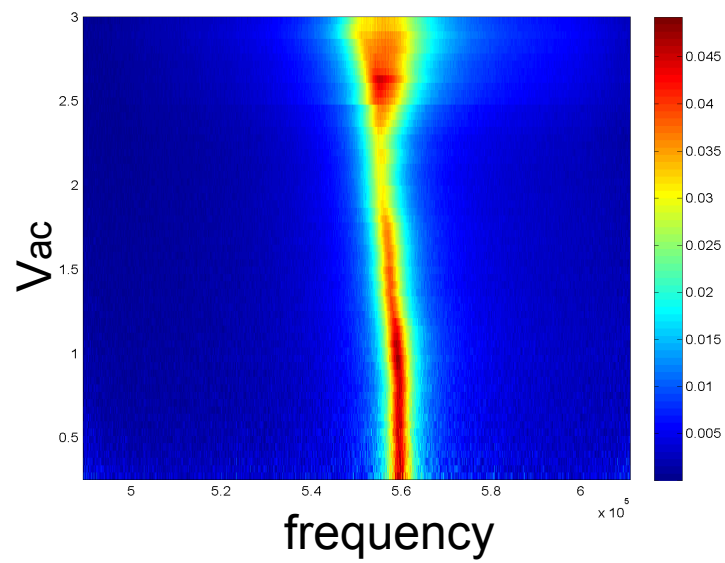


Increasing V_{ac}, high set-point

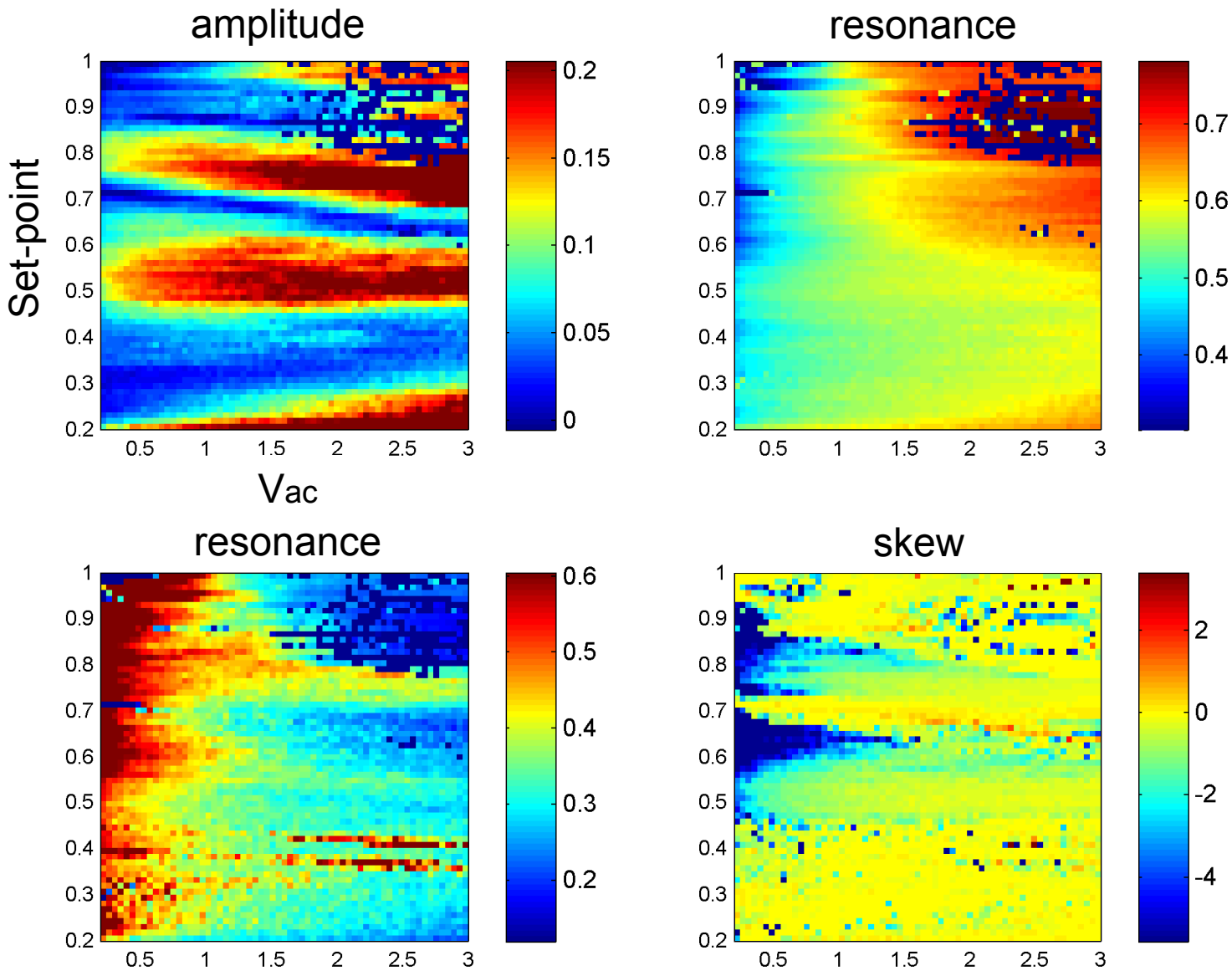


Increasing V_{ac}, intermediate set-point



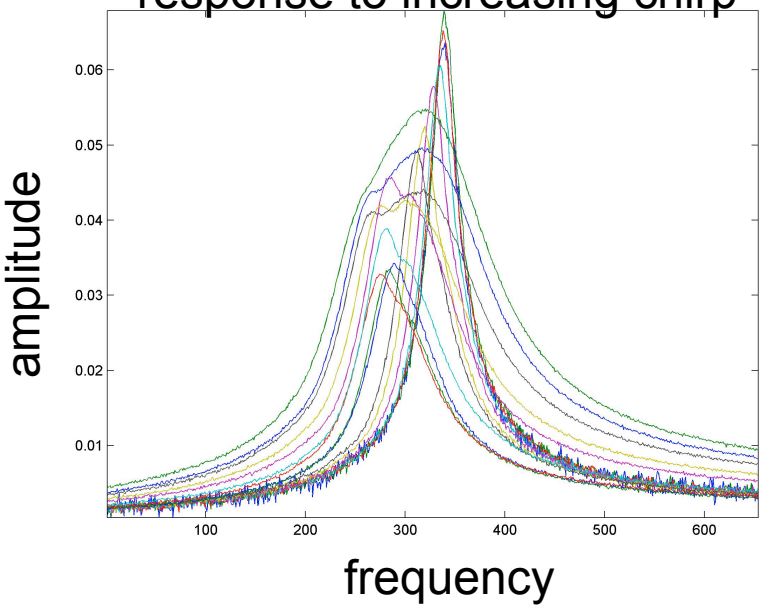


non-linear responses

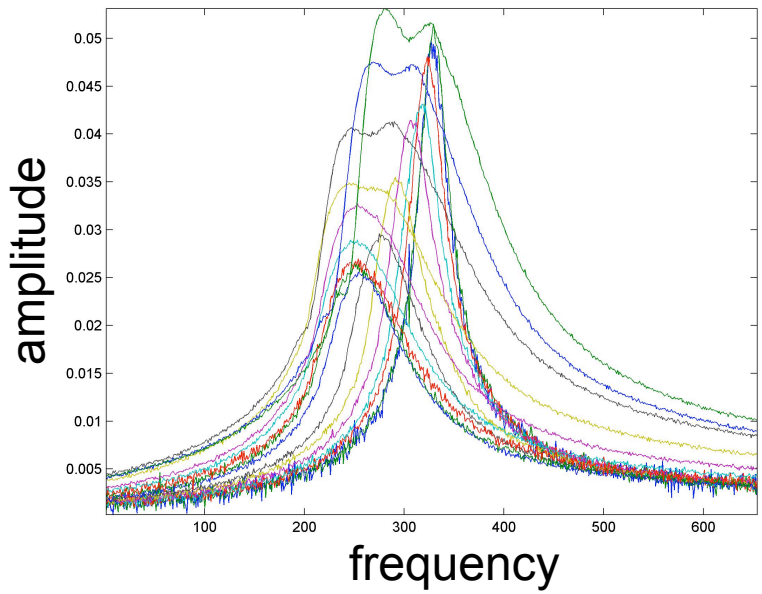


non-linear responses

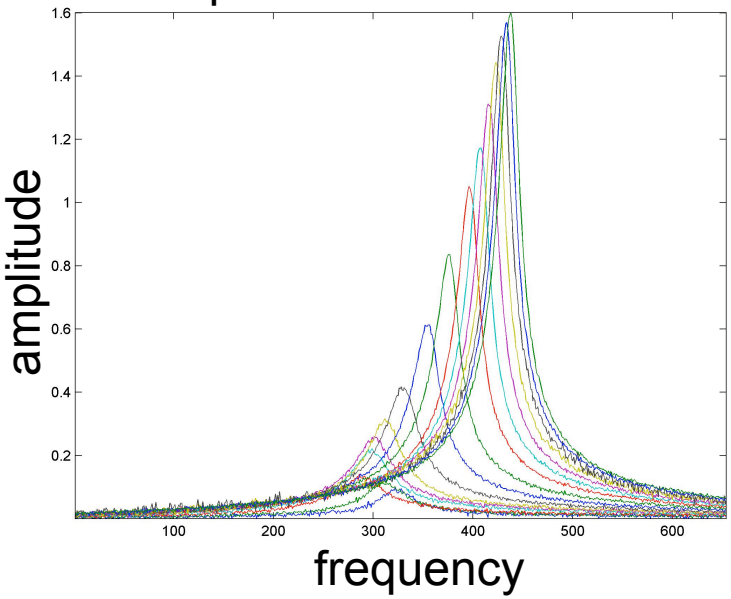
response to increasing chirp



response to decreasing chirp

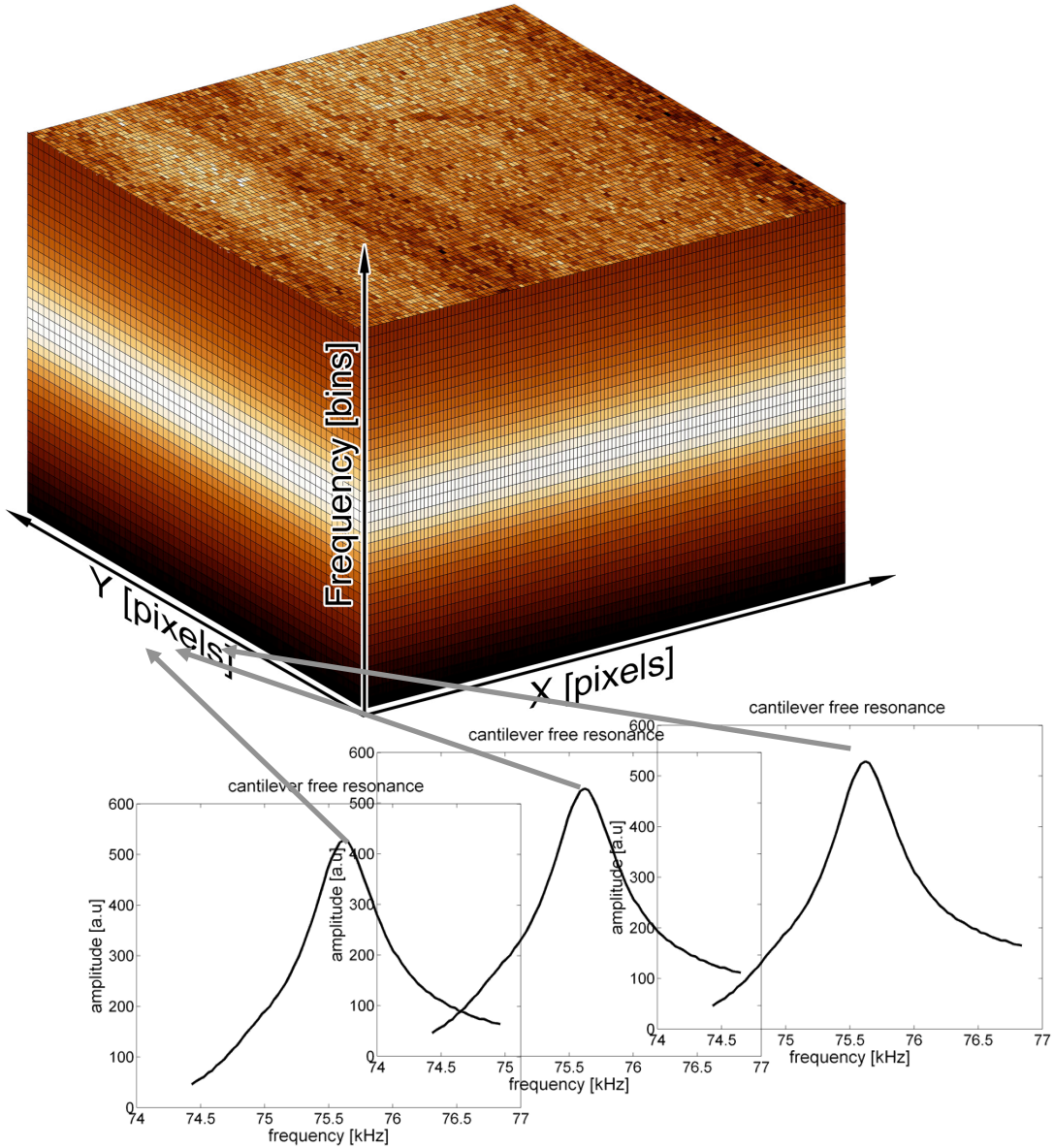


response to sinc function

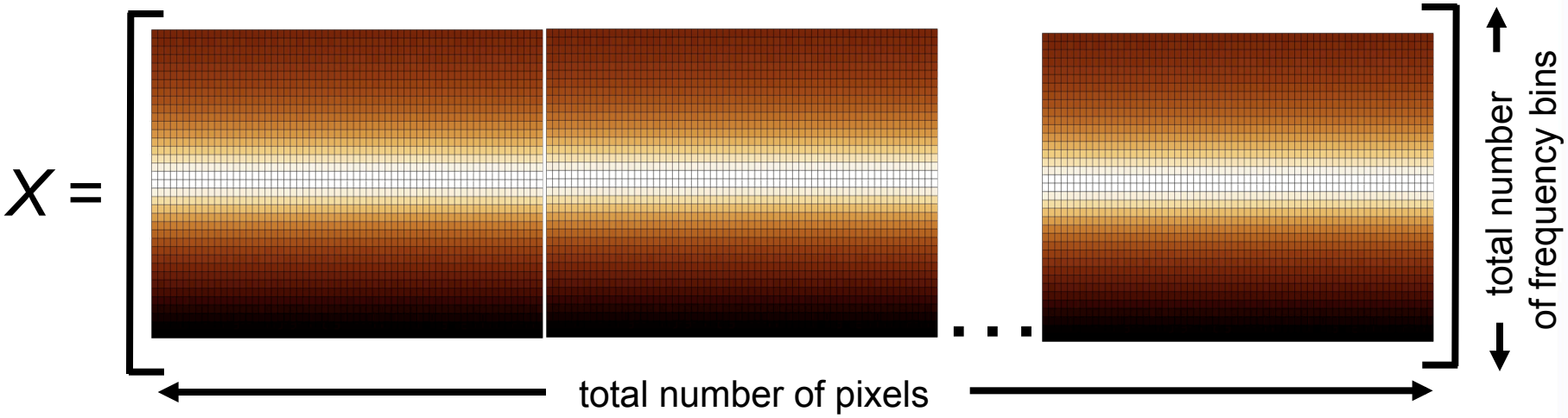


Principal Component Analysis (PCA)

principal component analysis



principal component analysis

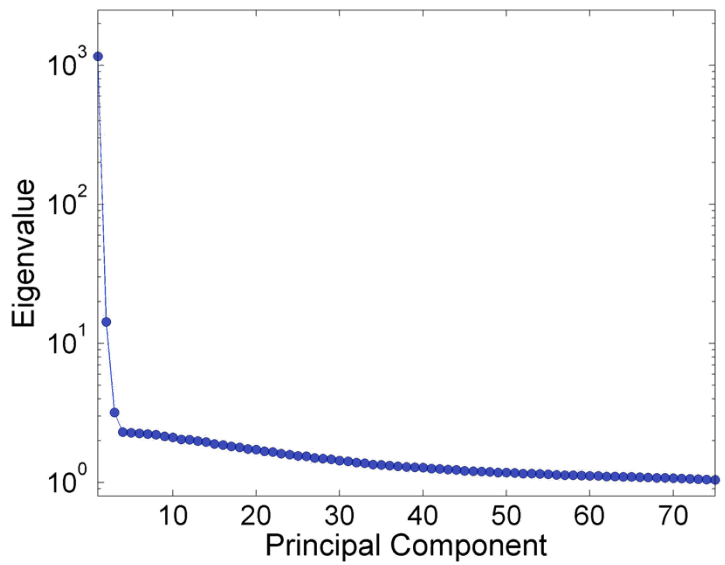


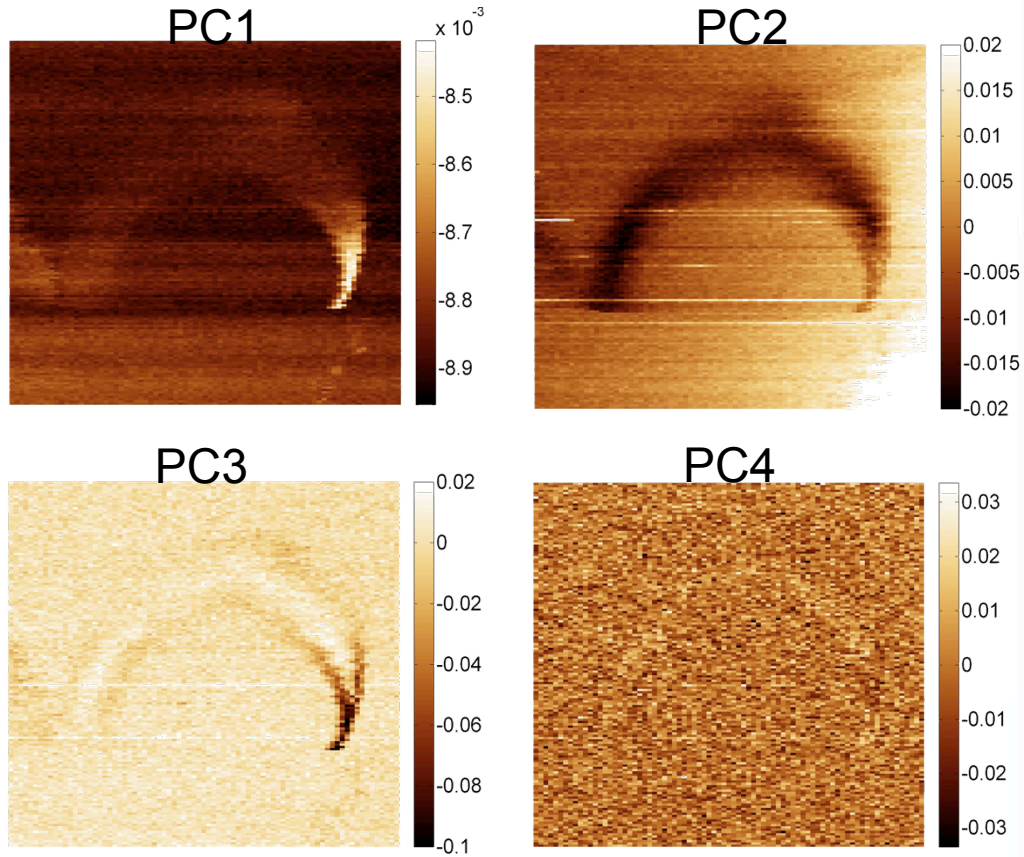
covariance matrix, $C = XX^T$, describes relationships between all pairs of spectra.
on-diagonal = variance (information)
off-diagonal = covariance (redundancy)

Goal 1: is to remove all redundancy. Therefore, we remove all off-diagonal elements

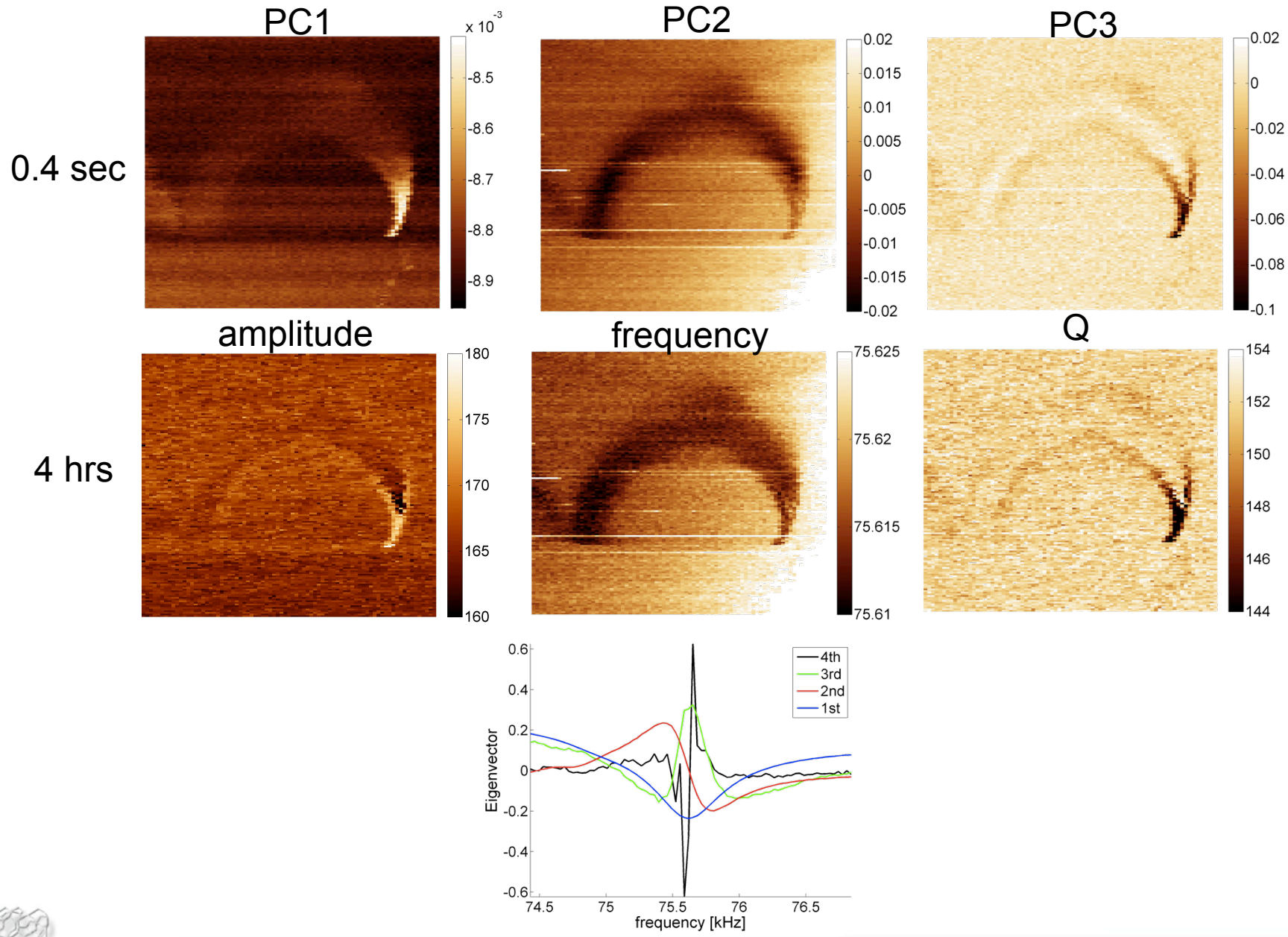
Goal 2: determine which elements contain the most information. Therefore, we rank on-diagonal elements by their magnitude, i.e. variance, i.e. information

principal component analysis





principal component analysis



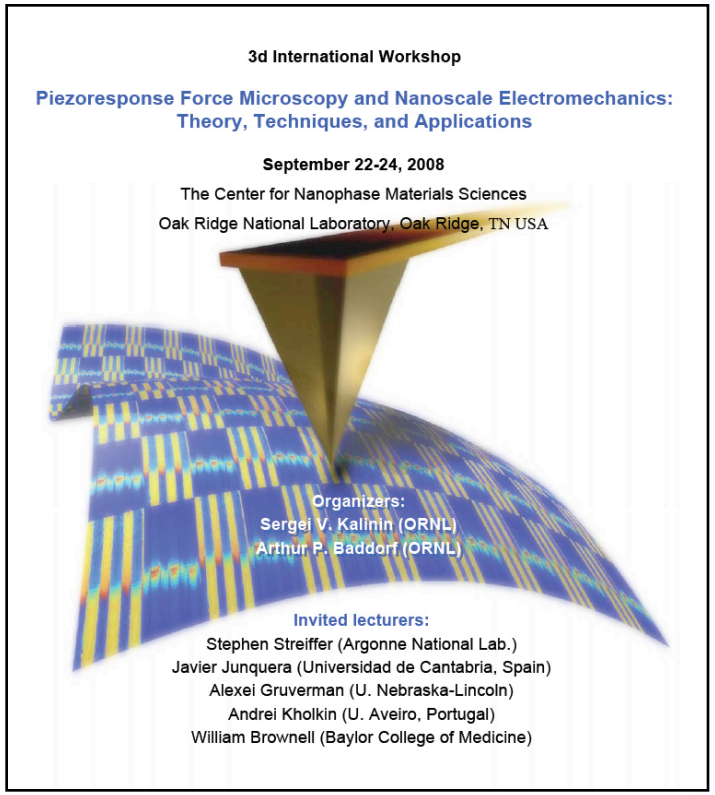
conclusion

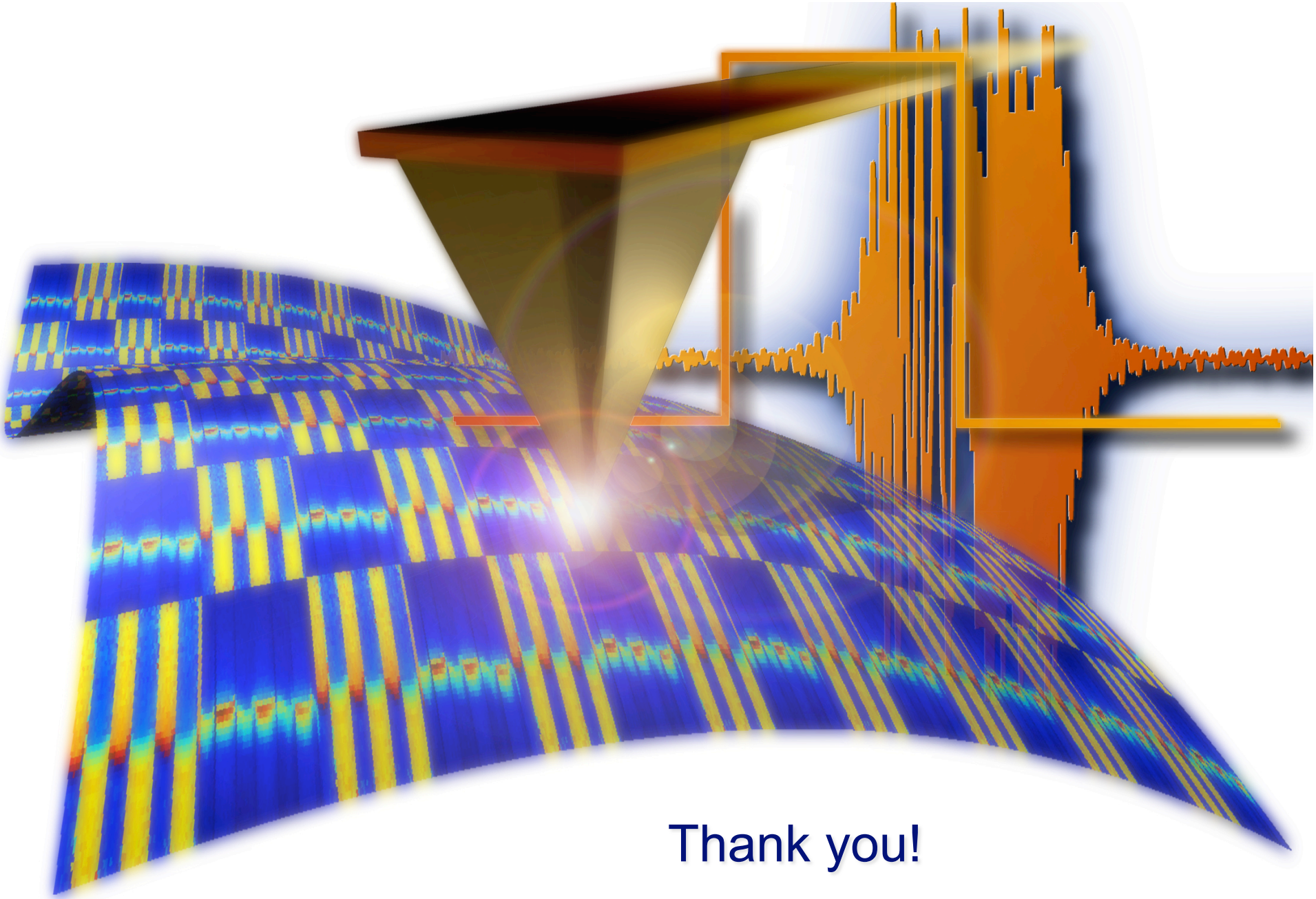
- Construct a BE waveform with desired duration and energy content
- PFM
  - Track frequency shifts
  - A new window into domain formation
- Nano-TA
  - Constant contact area
  - Detect the onset of melt or phase transition much sooner and less destructively
- MFM
  - Decouple conservative and non-conservative behavior
  - Increase resolution
- PCA
  - A rapid method for processing spectral-imaging data

availability band excitation SPM

Center for Nanophase Materials Sciences at ORNL

http:\\imaging.ornl.gov





Thank you!