



# Full-physics Integration

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PRISM Annual Review  
October 31 & November 1, 2011  
Purdue University

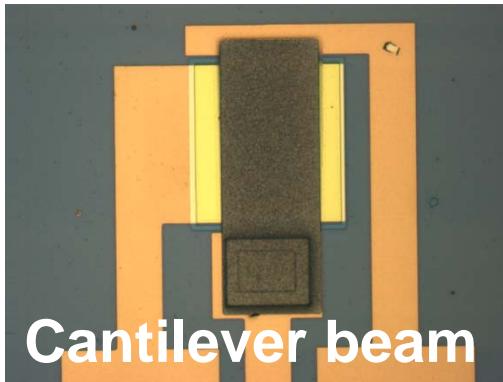
# Calibration, validation & prediction roadmap

## PRISM challenges

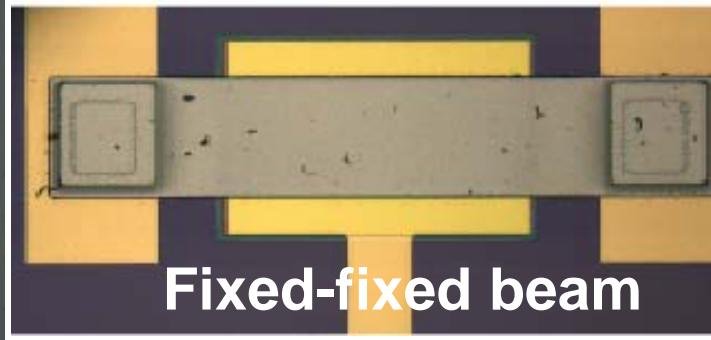
- Calibration and validation data from multi-devices
  - Device to device variability
- Multiple sources of uncertainty
  - In experiments and models
- Multiscale, multiphysics models
  - From electrons and atoms to devices
- Bayesian networks to calibrate, validate
- Use model form/confidence to inform predictions

# Experiments and Devices Overview

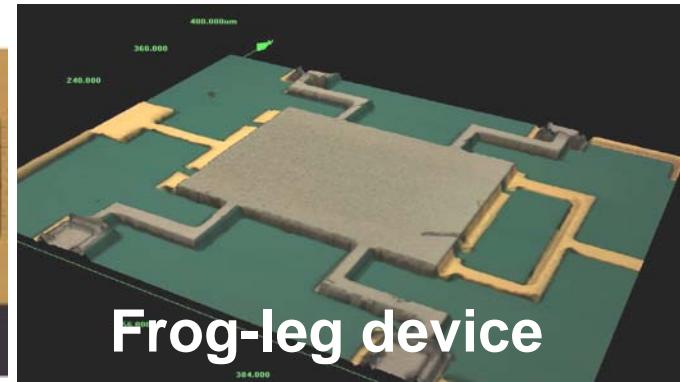
- ✓ Actuation and release voltage vs. cycles
- ✓ Charging for sustained contact (Prof. Alam)
- ✓ Dynamic beam response (Prof. Raman)
- ✓ Displacement vs. voltage for property extraction
- ✓ Geometry characterization



Cantilever beam



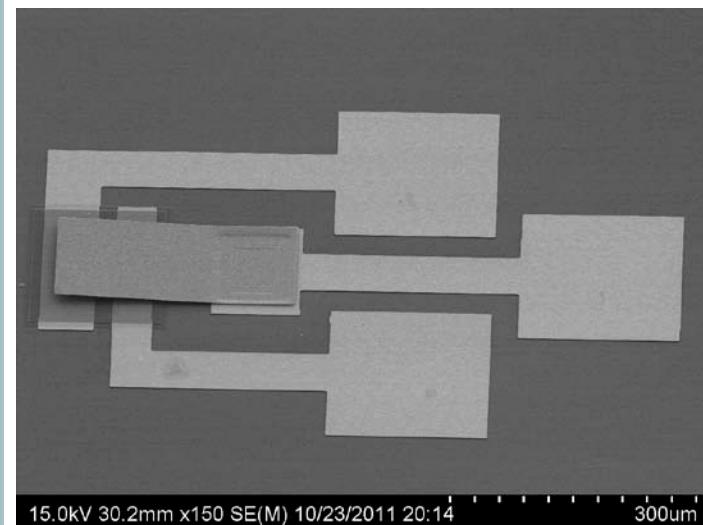
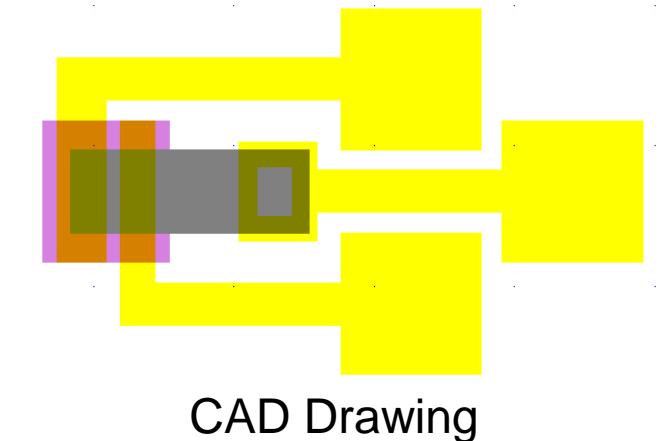
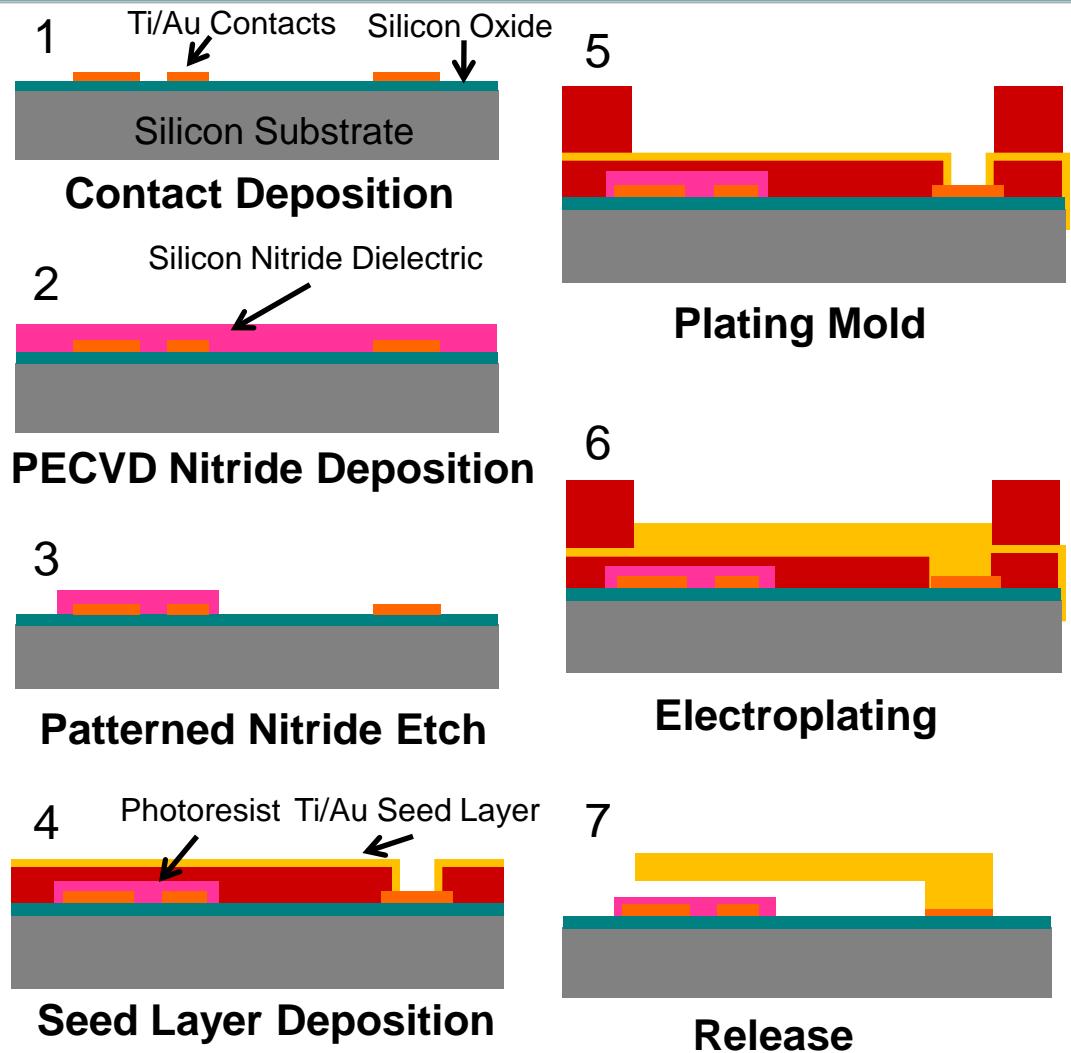
Fixed-fixed beam



Frog-leg device

Same fabrication process followed for all devices

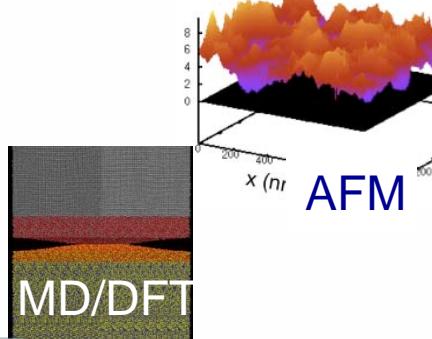
# Common Fabrication Process



# PRISM multi-physics integration

## Contact physics

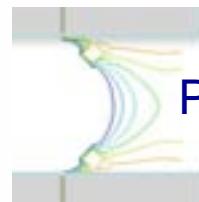
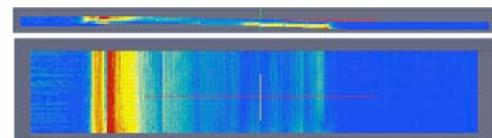
- Contact separation



MD/DFT

## Solid mechanics

- Elasticity & Creep

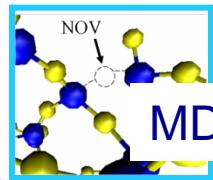


Phase field DD

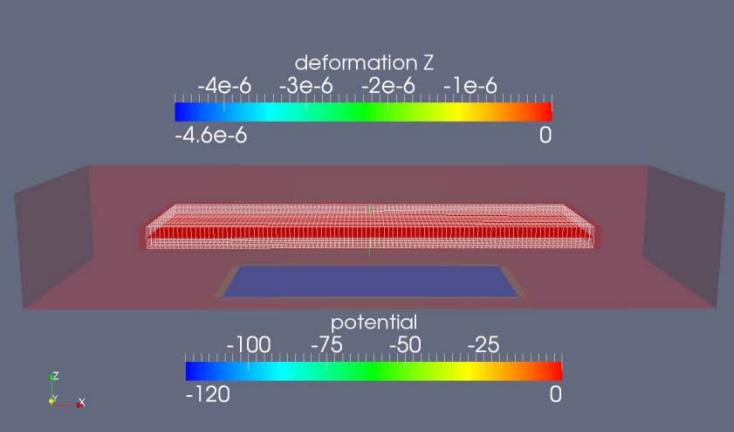
## Dielectric charging

- Defects in dielectric

Charge injection & transport

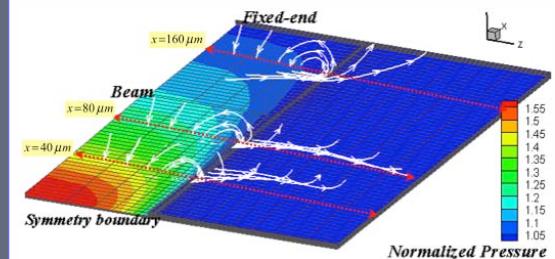


MD/DFT



## Fluid damping

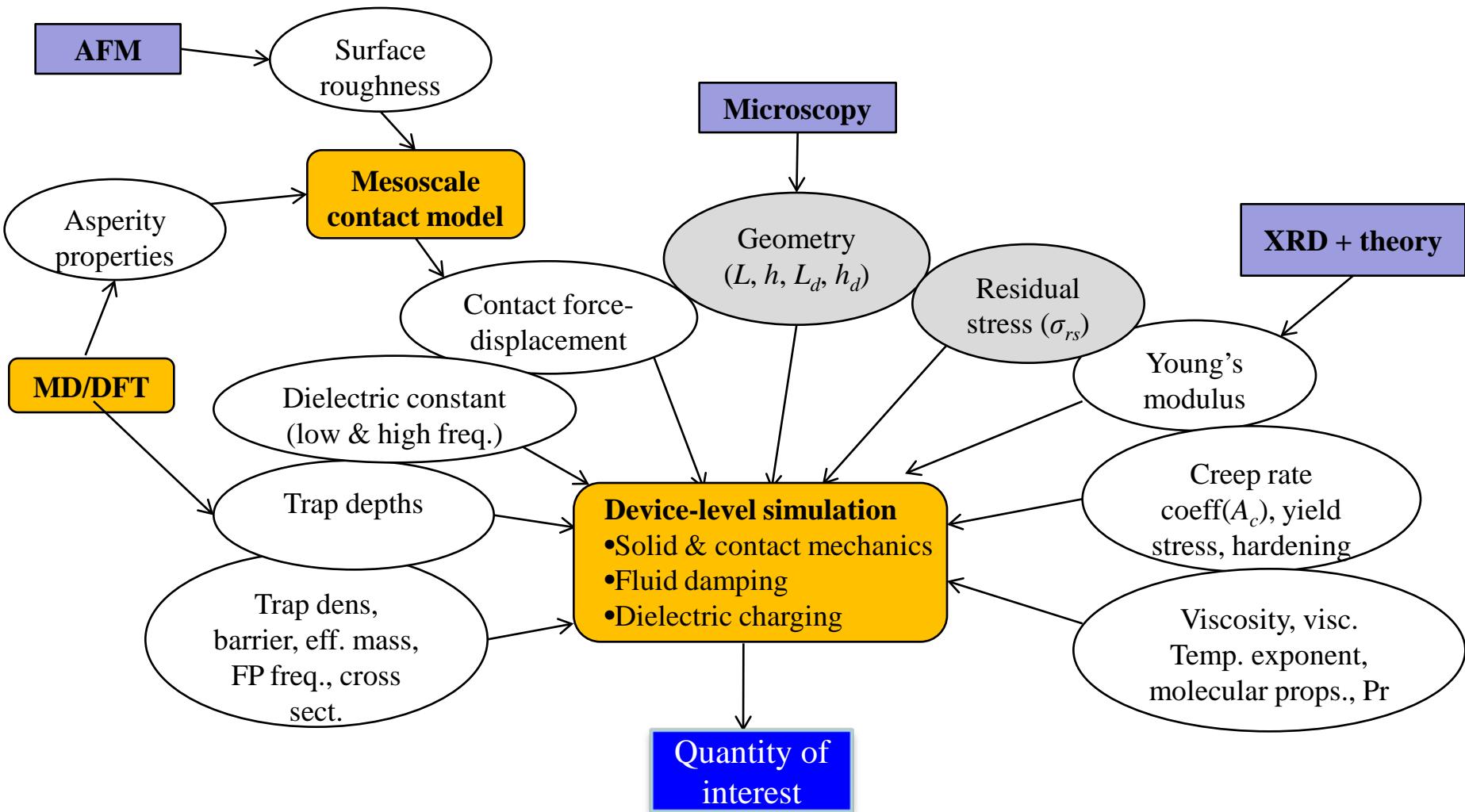
Continuum & rarefied



NS+ES-BGK

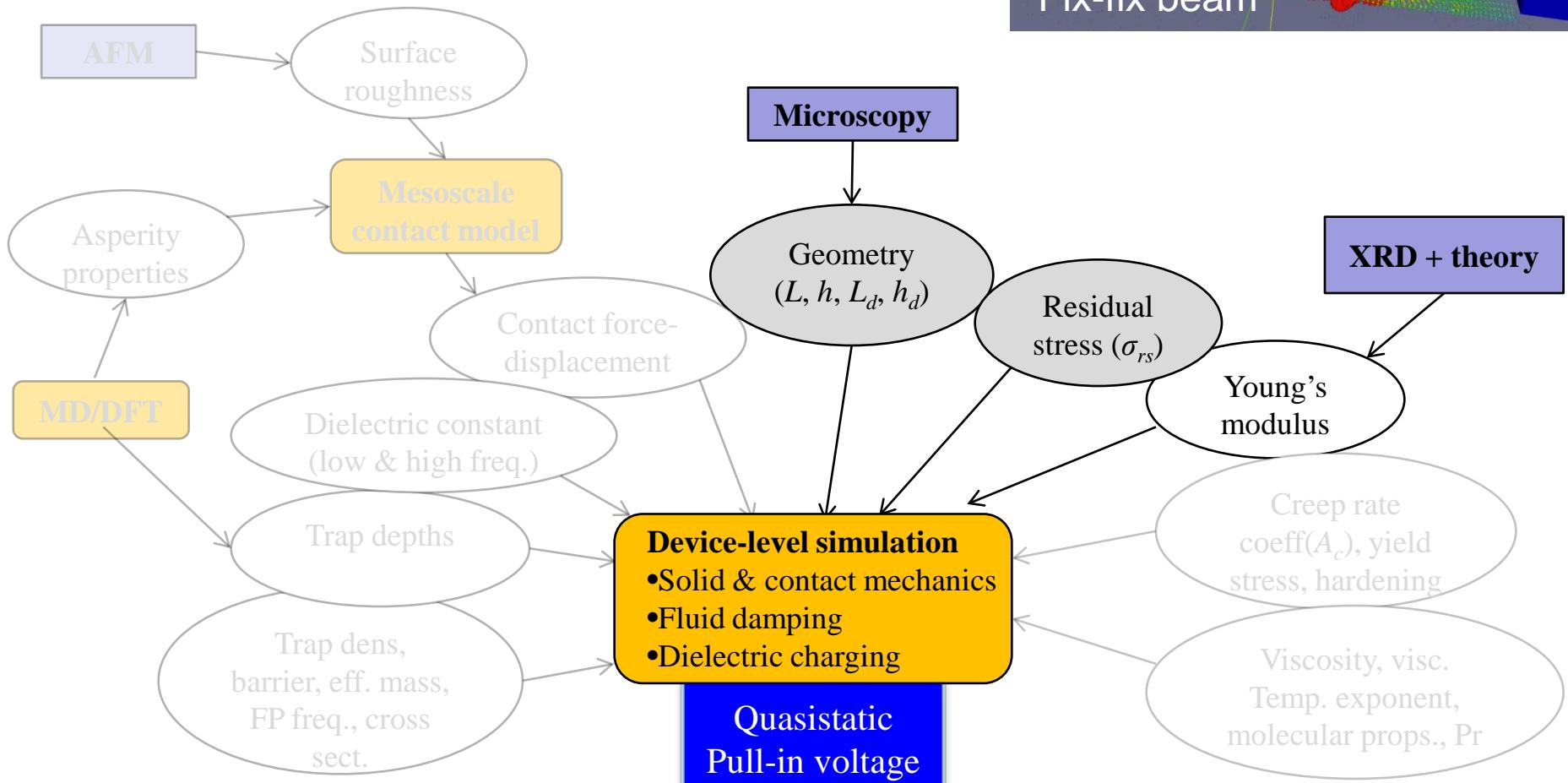
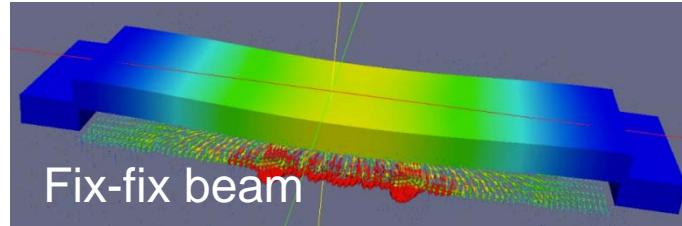
Quantity of interest

# Multi-physics, multiscale network

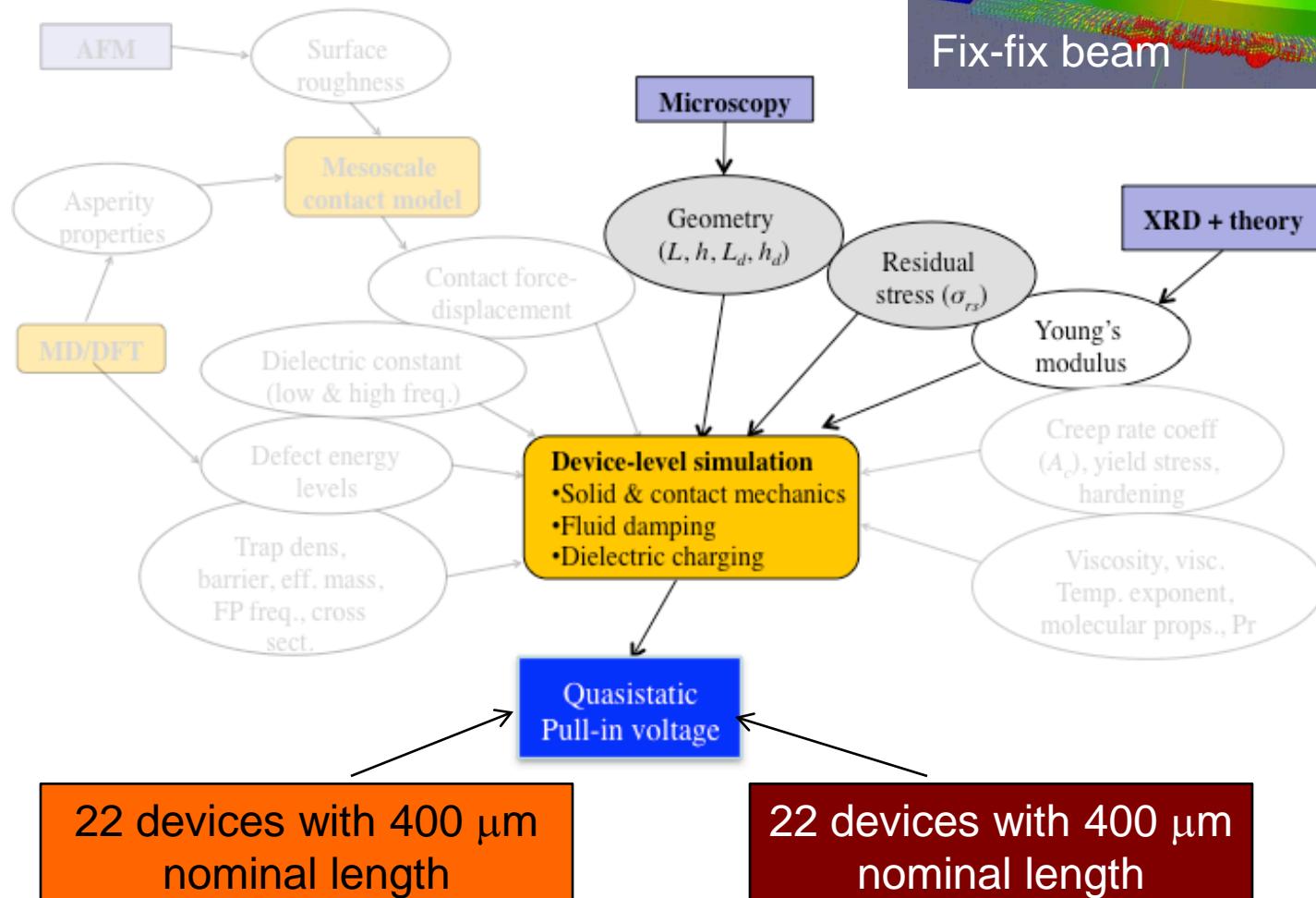
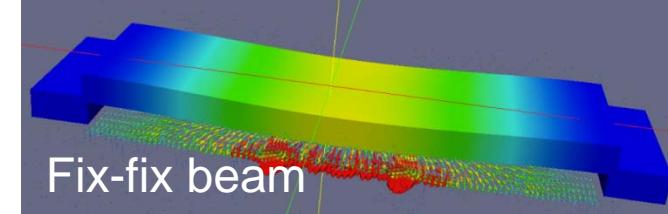


# GEN 5 optical measurements of pull-in voltage

- Calibration of residual stress
- Validation of membrane deformation



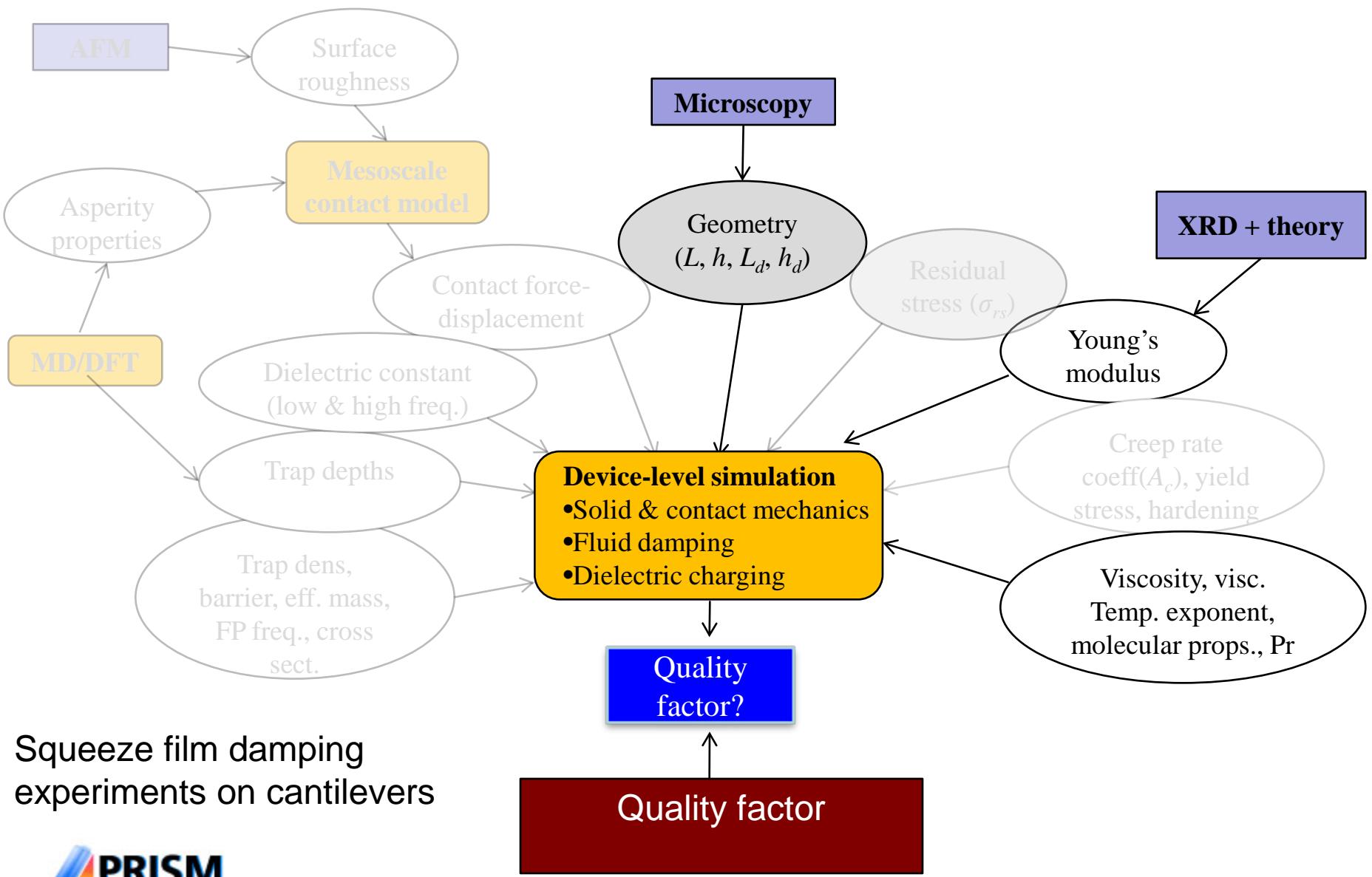
# GEN 5 pull-in



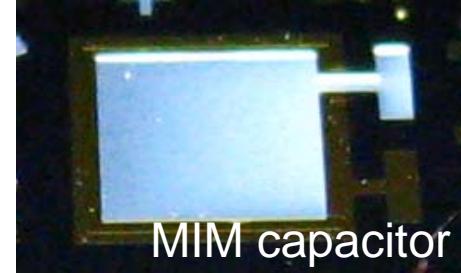
Step 1: Calibration of residual stress

Step 2: Validate membrane deformation model

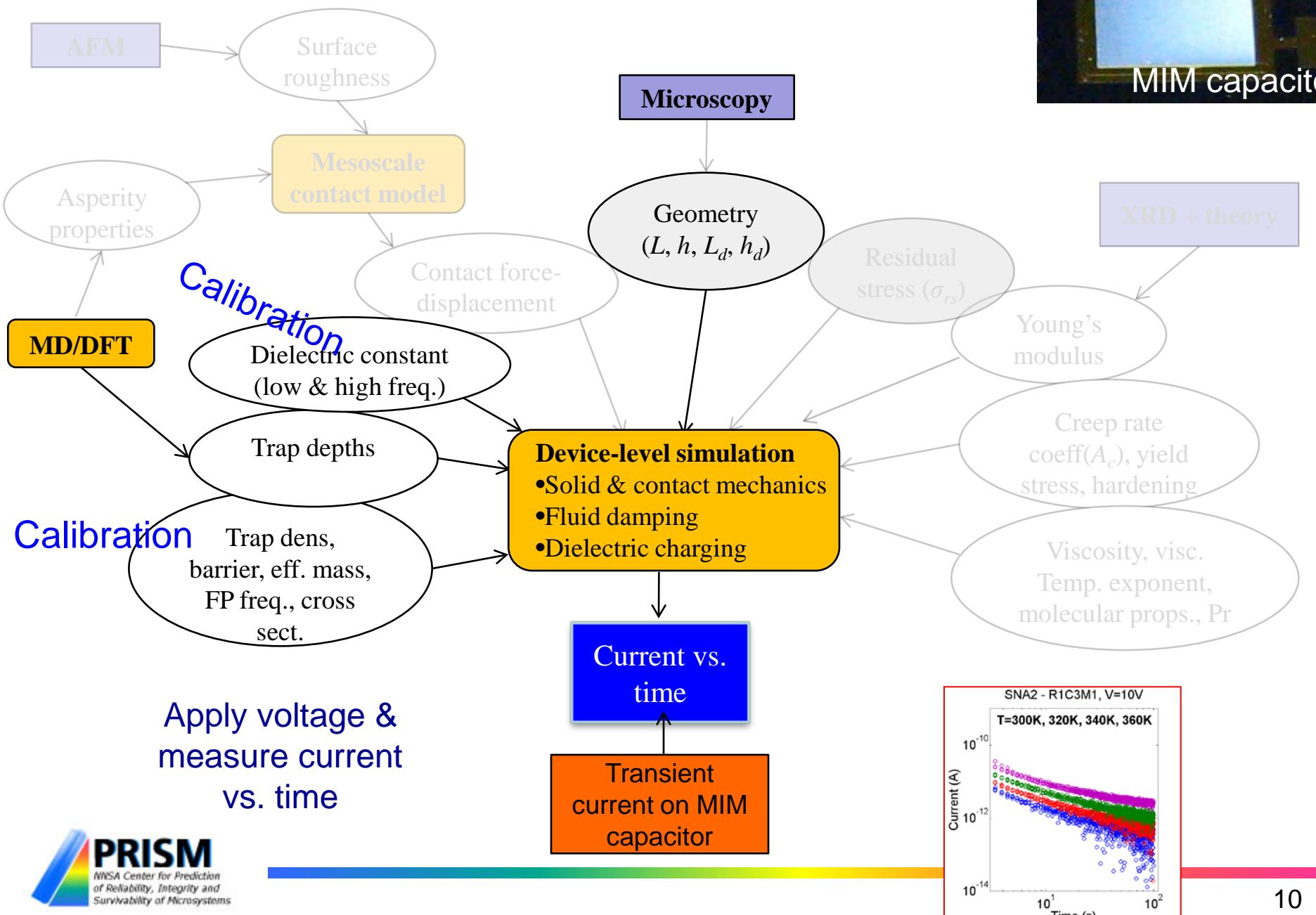
# Fluid damping validation



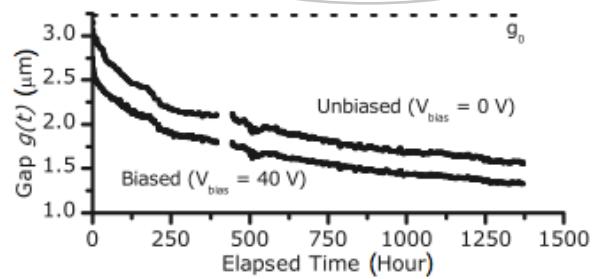
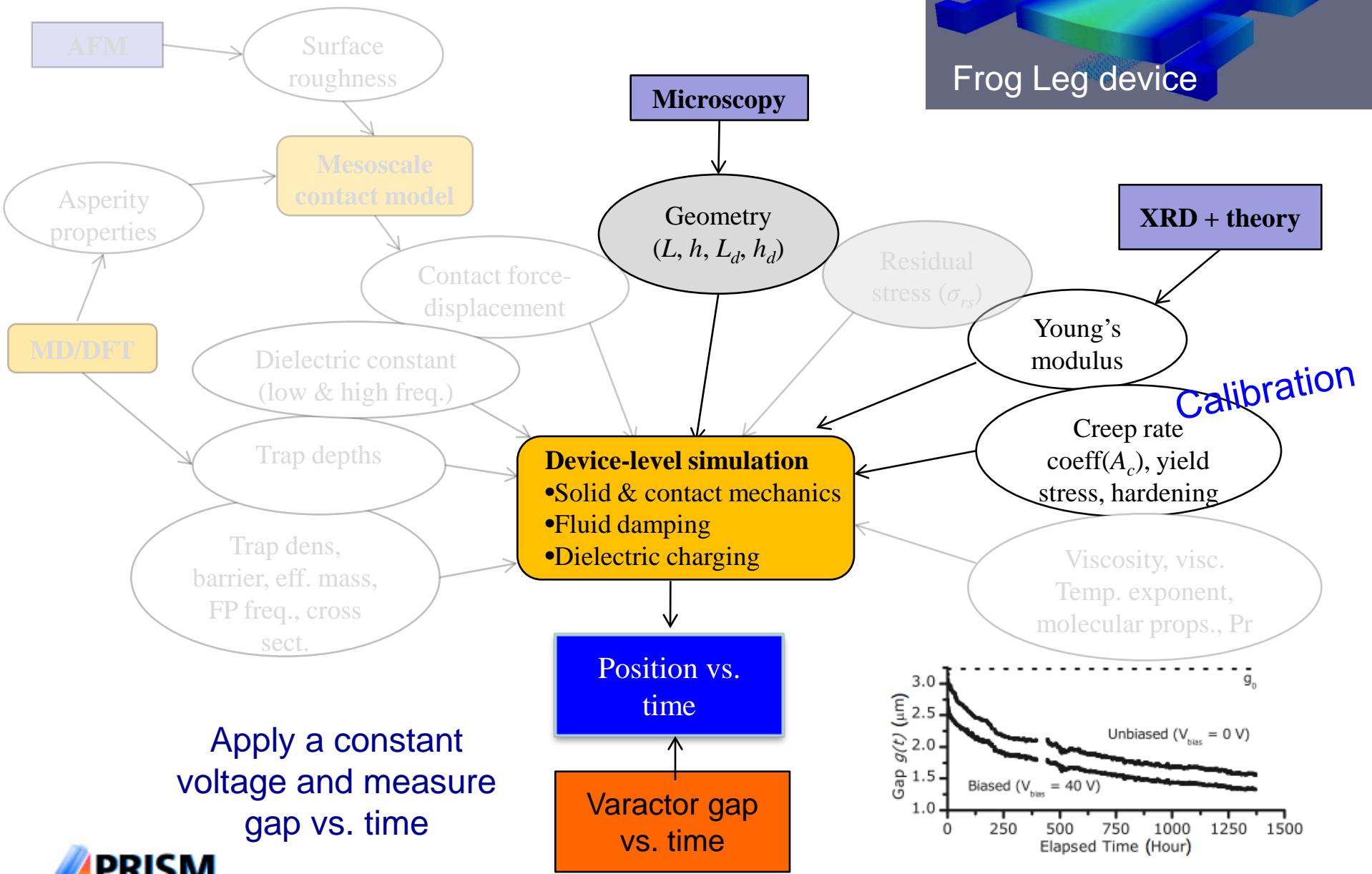
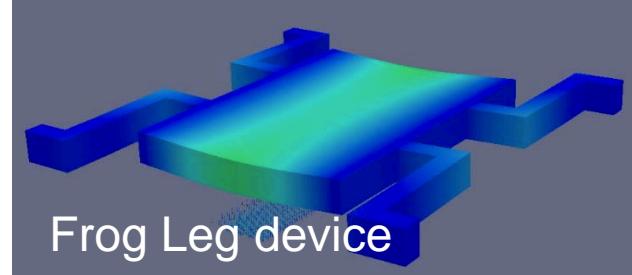
# Dielectric charging calibration



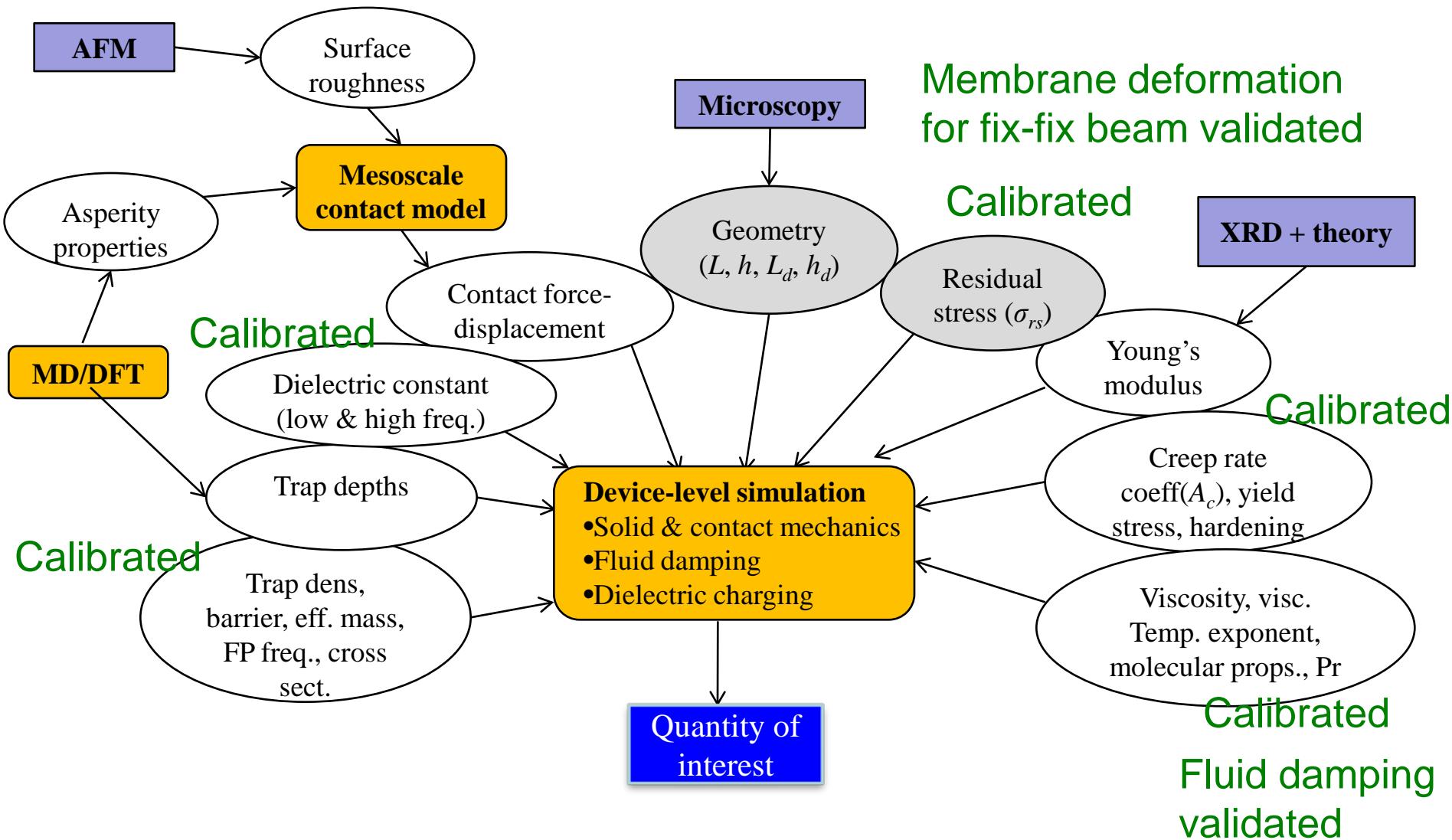
MIM capacitor



# Creep parameters calibration

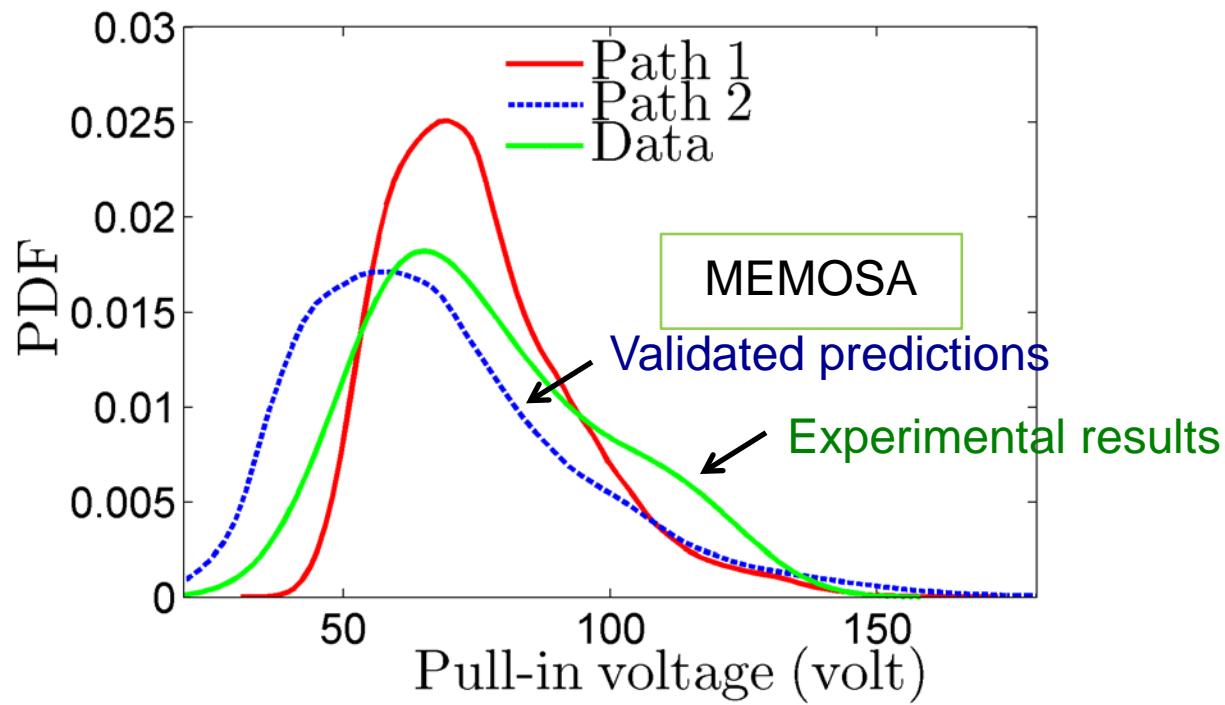


# Multi-physics, multiscale network



# Pull-in voltage prediction: 500 $\mu\text{m}$ GEN5 devices

- Residual stress calibrated using 22 devices with 400  $\mu\text{m}$  length
- Model validated using 22 additional 400  $\mu\text{m}$  devices
  - Confidence factor of 0.8
- Prediction for 500  $\mu\text{m}$  vs. experimental measurements



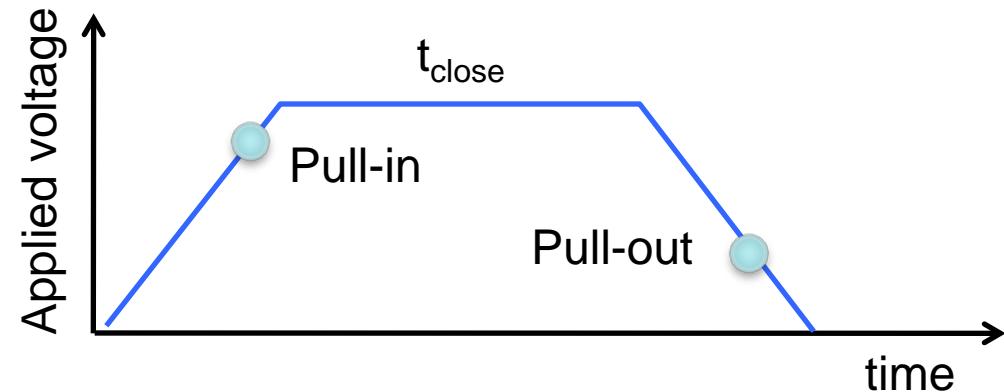
# Remaining validation via cantilever experiments

## Remaining validation tasks:

- Dielectric charging model in switch
- Contact model
- Creep model

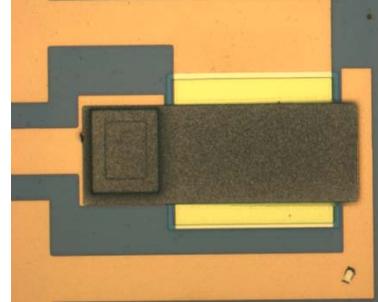
## Calibration & validation status

MEMOSA calibration & validation status	Calibration	Validation
Beam deflection	Green	Green
Fluid damping	Green	Green
Dielectric charging	Green	Red
Contacts	Green	Red
Creep	Green	Red

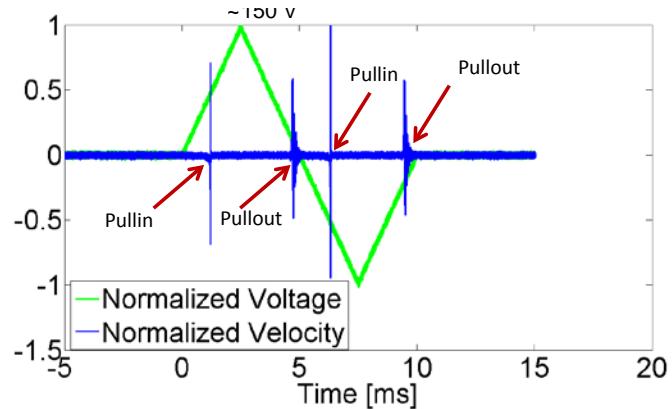


- Pull-in and pull-out from optical measurements
- Varying  $t_{close}$  allows use to independently validate contact and charging models
- Long-time deformation for creep validation

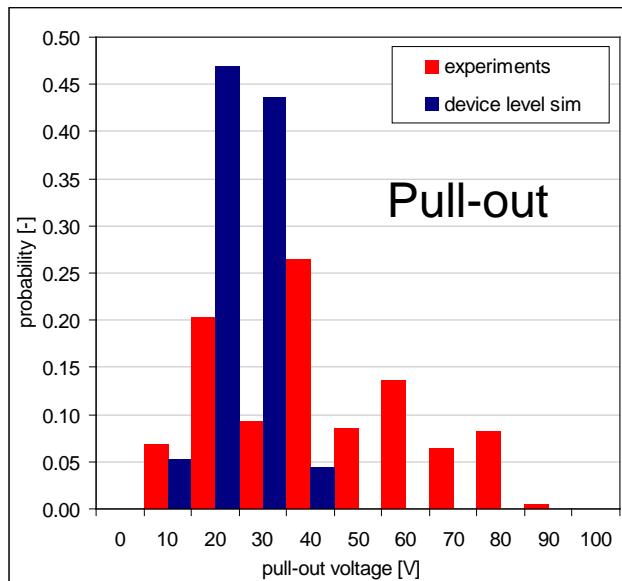
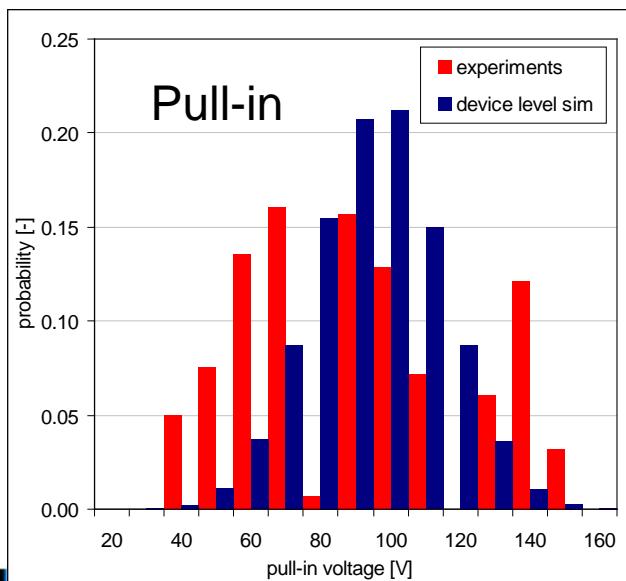
# Predictions on cantilevers



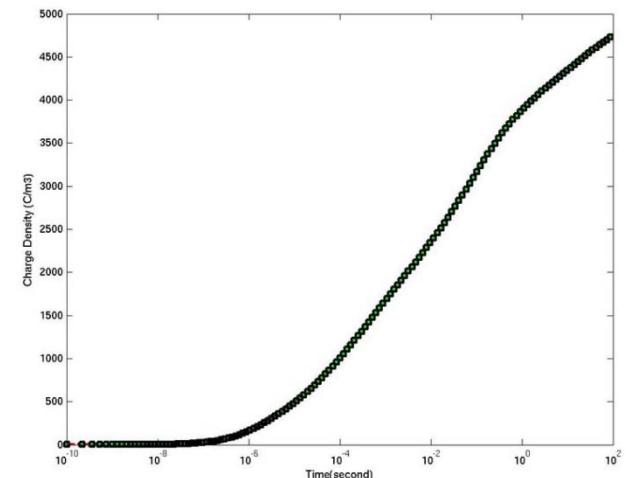
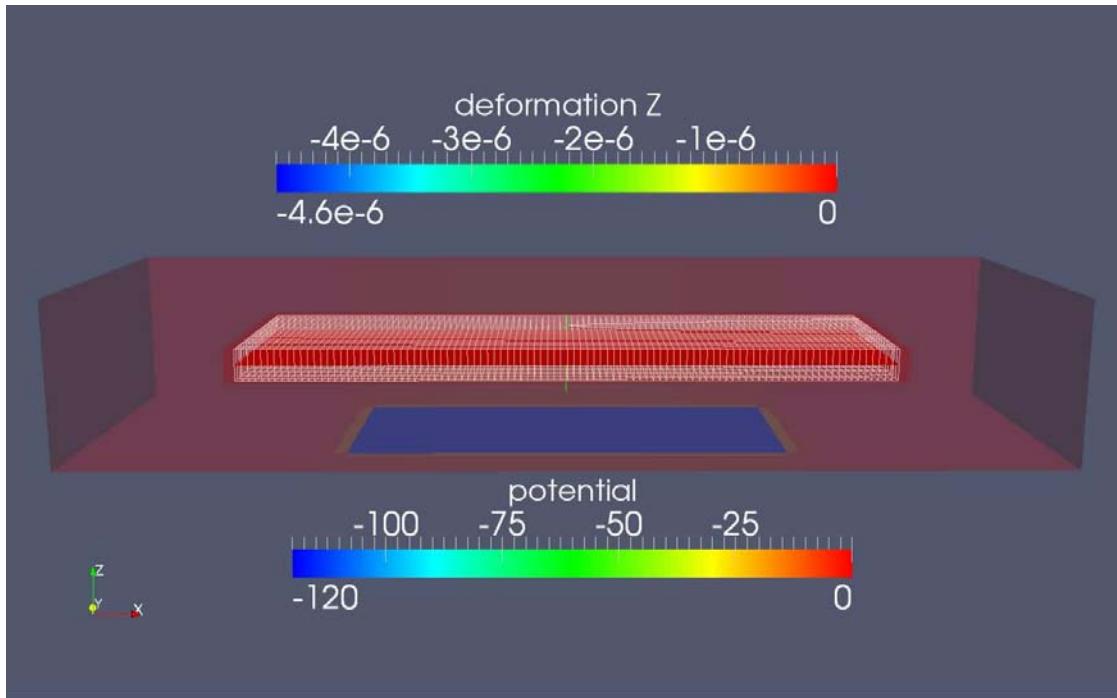
- Initial device-level predictions vs. experiments
  - Models are calibrated but not validated



Applied voltage 150 V  
Multiple repetitions on 7 devices



# Full physics simulations of fix-fix beam

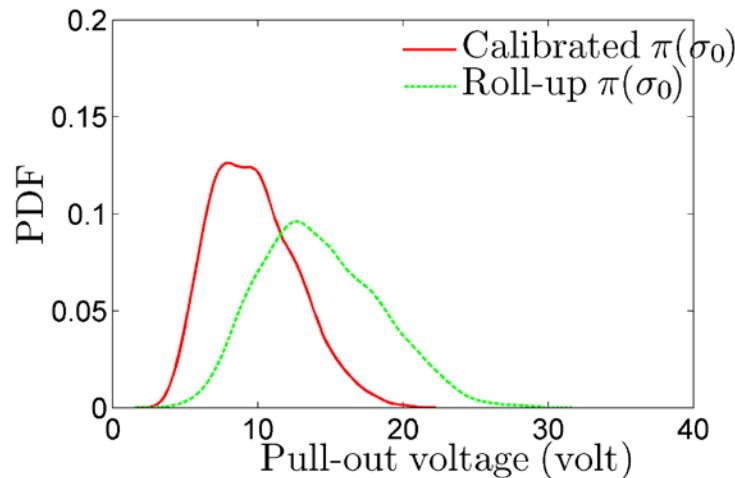


# Full physics simulations of fix-fix beam

## Calibration & validation status

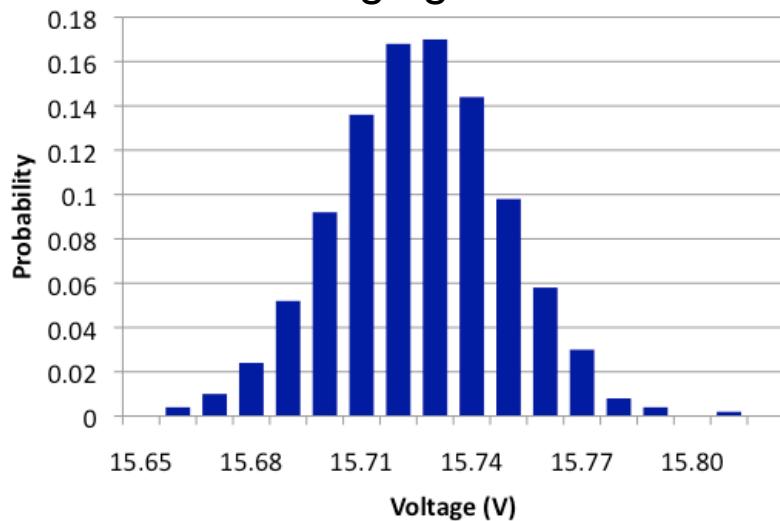
MEMOSA calibration & validation status	Calibration	Validation
Beam deflection	Green	Green
Fluid damping	Green	Green
Dielectric charging	Green	Red
Contacts	Green	Red
Creep	Green	Red

## Pull-out voltage predictions for PRISM device



## Role of dielectric charging on pull-out ( $V=120$ V)

Charging for 5 ms



Charging for 50 s

