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Characterization of an AlGaN/GaN Electrostatically Actuated Cantilever using Finite Element Method

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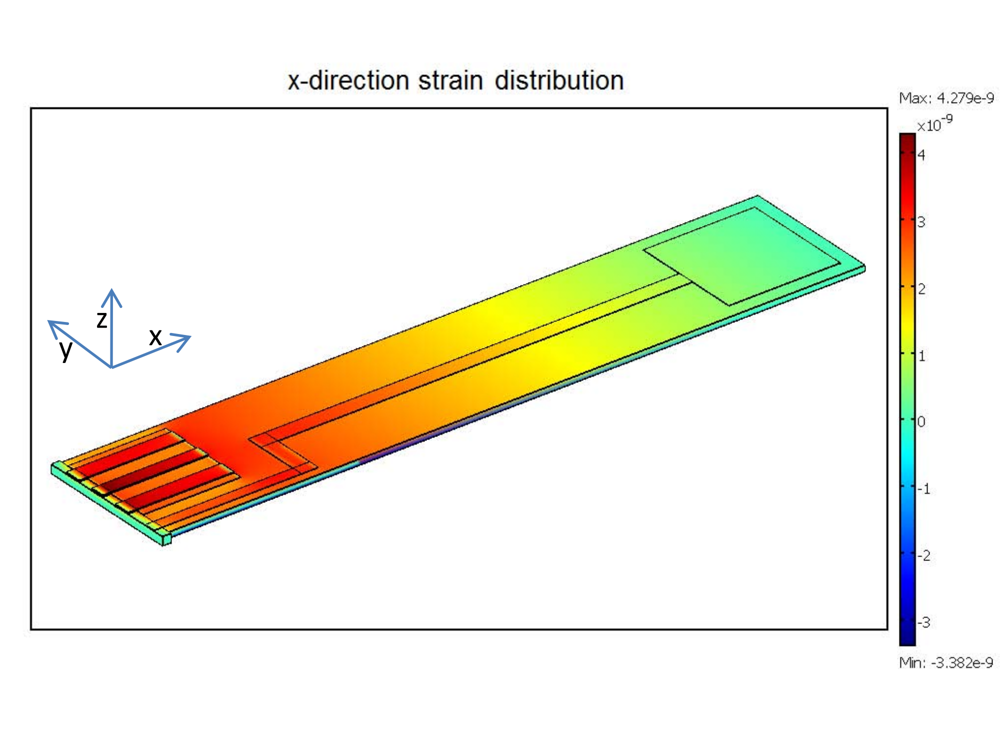
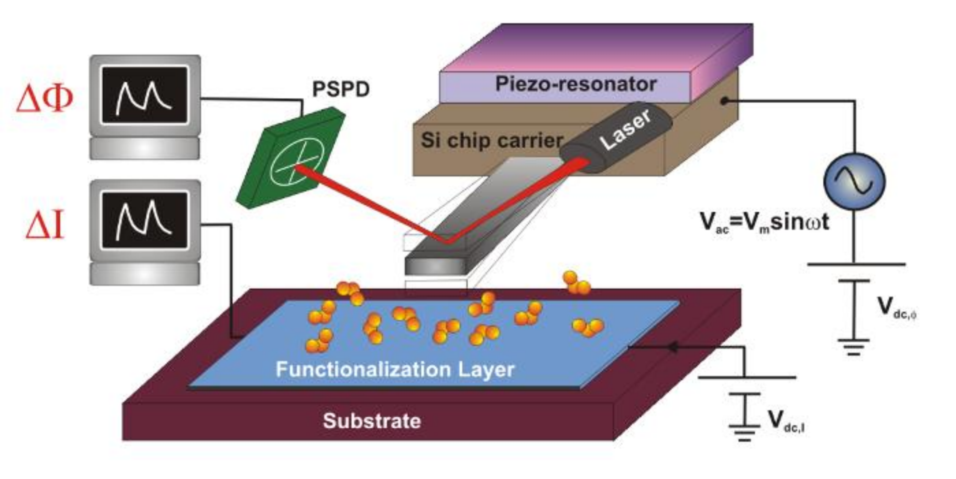


Introduction

- MEMS cantilevers used in the sensing field:
  - Chemical [1]
  - Biological [2]
  - Explosives [4]
- Optical transduction
  - Bulky
  - Cannot integrate into miniaturized sensors
  - High power consumption



Introduction

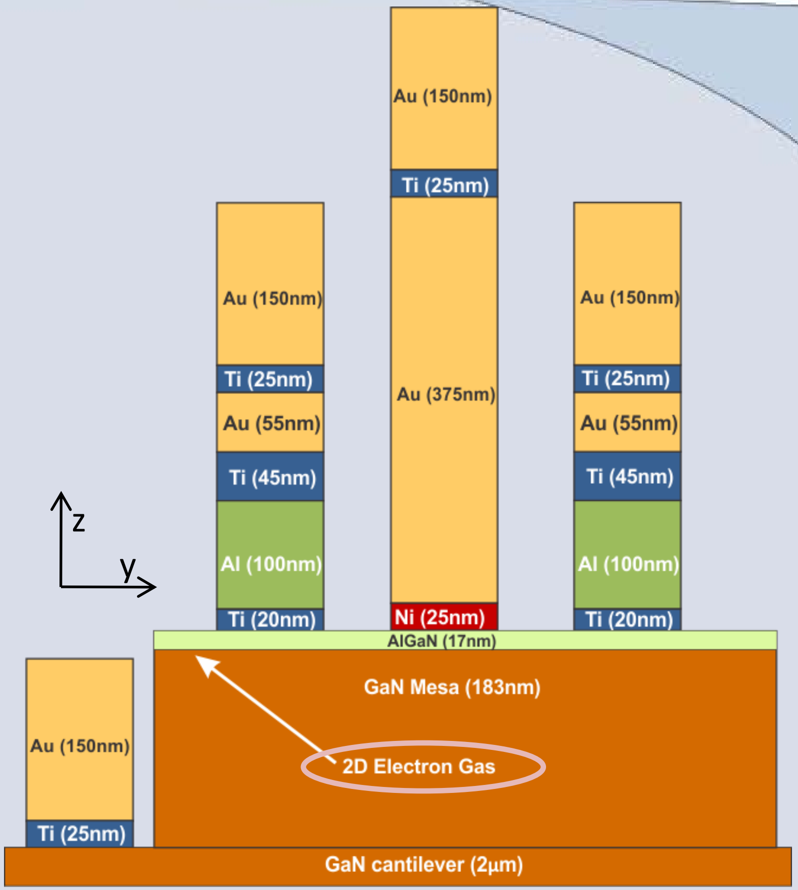
- Electrical transduction on MEMS cantilevers
  - Piezoresistive
    - Uses piezoresistors fabricated at the base
    - Resistance changes due to strain variation [4]
    - More noise
  - Piezoelectric

Introduction

- Electrical transduction on MEMS cantilevers
  – Piezoresistive
  – Piezoelectric
    - AlGaN/GaN HFET embedded at base of microcantilever
    - Source-drain current is significantly affected by bending [6]
    - Wider bandgap
      – Can operate in high temperature/harsh environments
    - Higher sensitivity

Introduction

- AlGaN/GaN Heterostructures:
  - Large piezoelectric and spontaneous polarization properties
    - Creates highly localized 2D electron gas (2DEG) at the interface [7]
    - Polarization properties are dependent on strain [7] [8]
    - Knowing the strain distribution at the interface allows accurate calculation of source-drain current

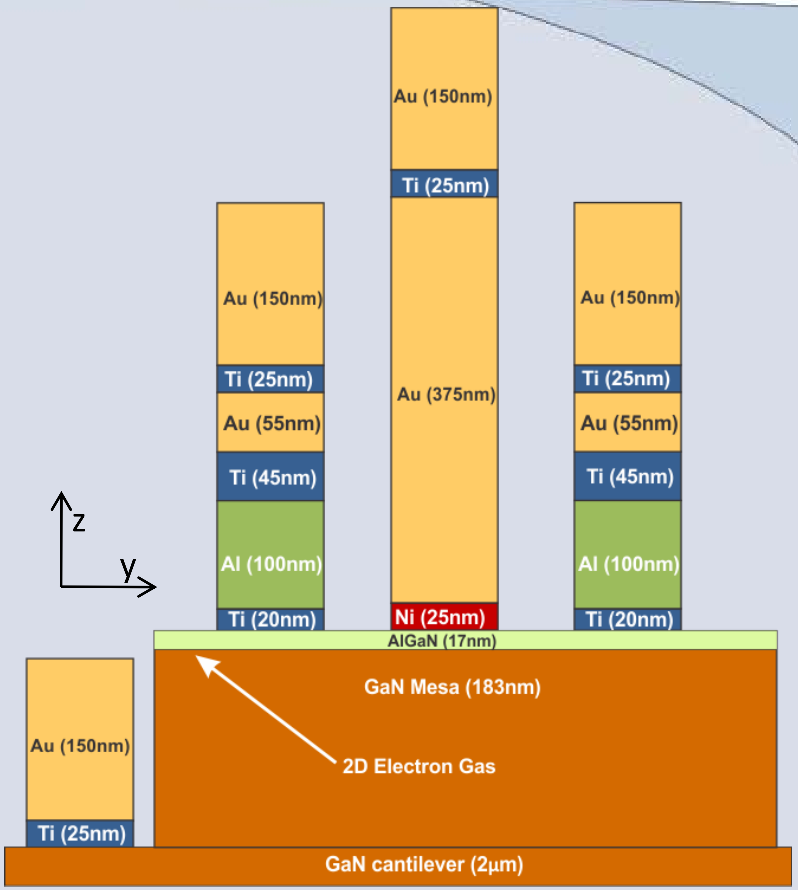


Cross section of the cantilever's metal stack

Fabrication

Cantilever specifications:

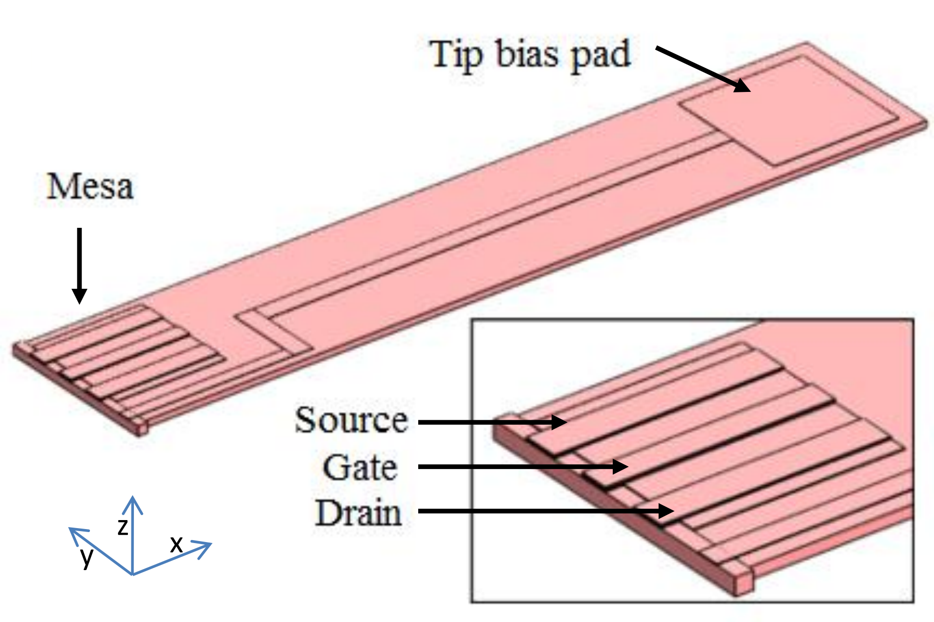
- 250µm × 50µm × 2µm
- AlGaN/GaN layers grown on Si(111)
- AlGaN layer is 17.5nm
- Mesa height is 217nm to ensure complete AlGaN/GaN down etching.
- Metal stack (seen right) followed by rapid thermal annealing
- Through wafer Si etch performed using “Bosch” process



Cross section of the cantilever’s metal stack

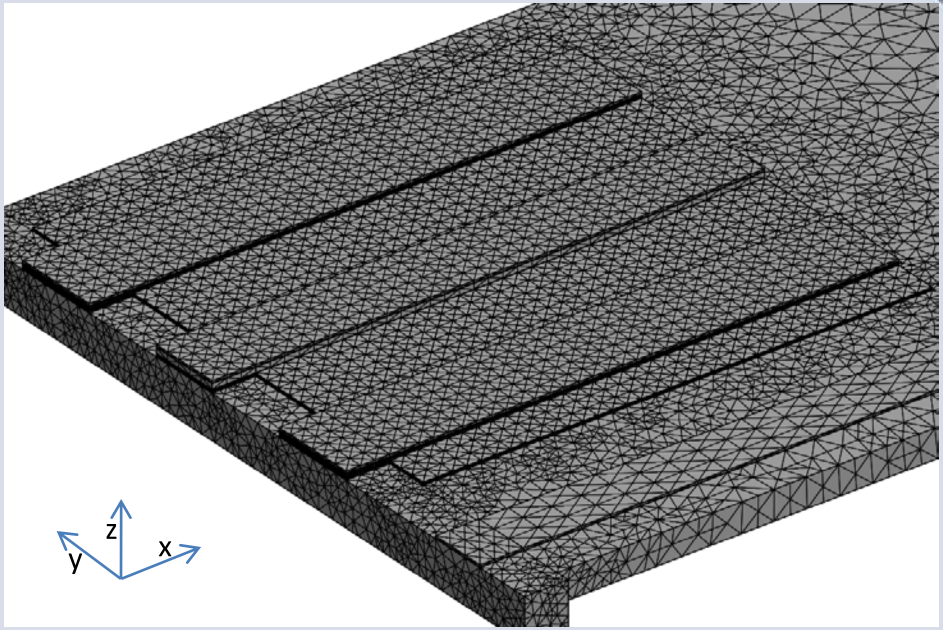
Simulation

- Shown at right is the model used.
- A 35µm × 35µm mesa is situated at the base.
- Source, gate, and drain metal stacks are placed on top of mesa.
- All metal stack layers are modeled to ensure accurate strain distribution output



Simulation

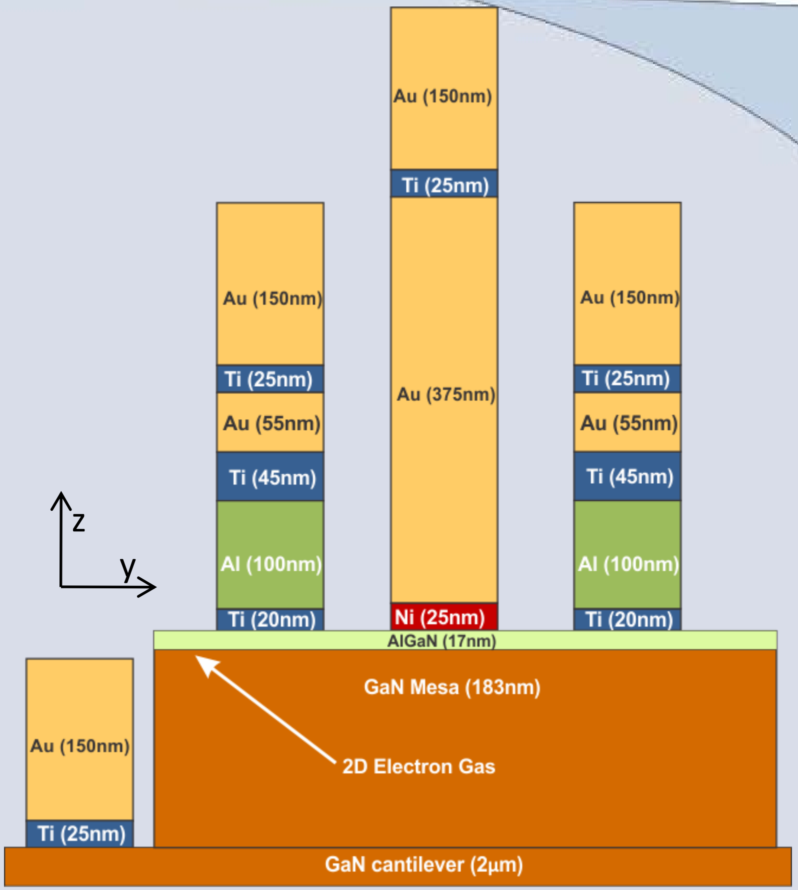
- The model used has very thin layers on a large structure
- Very large aspect ratio in metal stack creates meshing problems
- Mapped/swept meshing is used over all metal stacks
  - Manual meshing: 4 min per static simulation
  - Auto-mesh: runs out of memory
- All simulations use the default Lagrange-Quadratic type elements.



Mapped meshing about the mesa area

Simulation - Static

- Static simulations were run to examine strains about the mesa
- Effects of metal stacks examined
- Strain distributions can later be used to find a strain/current relationship.
- 2DEG formation depends on both *x* and *y*-strains as described by piezoelectric polarization



Cross section of the cantilever's metal stack

Simulation - Static

- Piezoelectric polarization:[8]

$$P_{PE} = e_{33}\varepsilon_z + e_{31}\left(\varepsilon_x + \varepsilon_y\right)$$

ε_x ,ε_y ,ε_z = *x*, *y*, and *z*-direction strains

e_{33}, e_{31} = piezoelectric constants for $Al_xGa_{1-x}N$

Simulation - Static

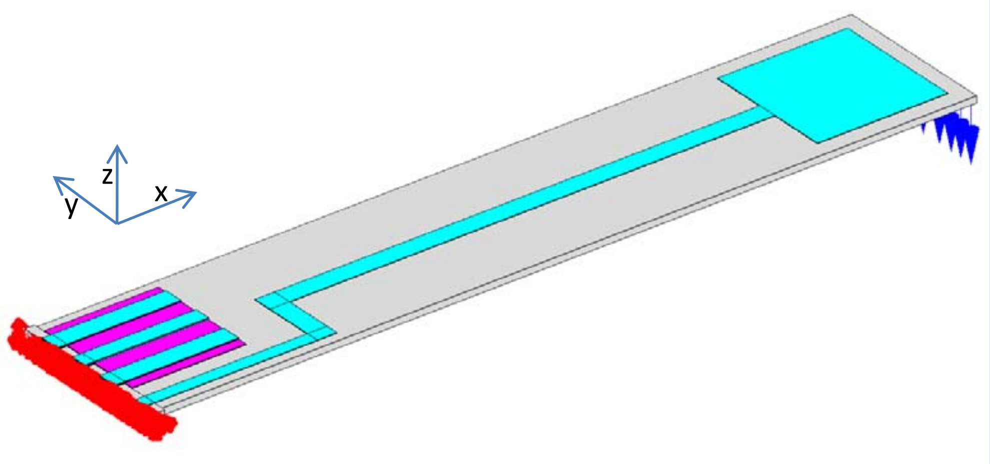
- Spring Constant:

$$k = \frac{Ewt^3}{4L^3}$$

- Strain:

$$\varepsilon = \frac{6F(L-x)}{Ewt^2}$$

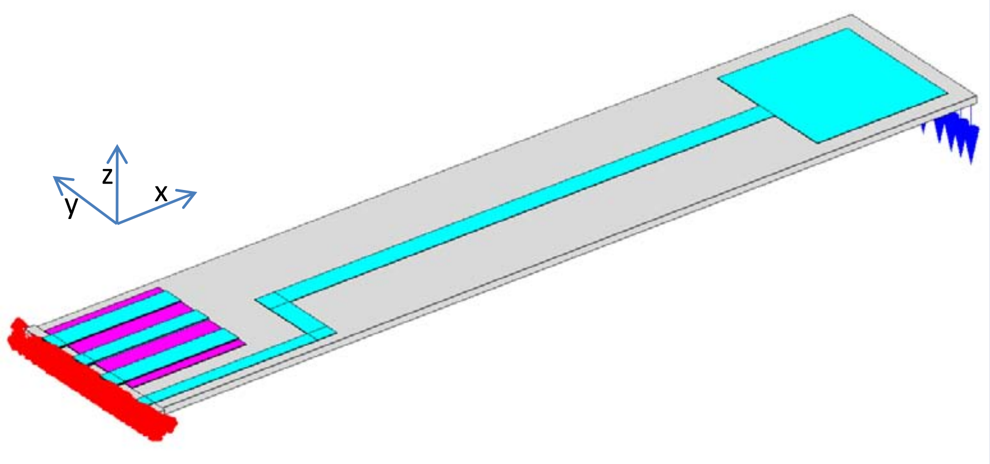
- E = Young’s Modulus
- w = width
- t = thickness
- L = length
- F = force
- x = length of strain measurement



Constraints and force conditions applied to the model

Simulation - Static

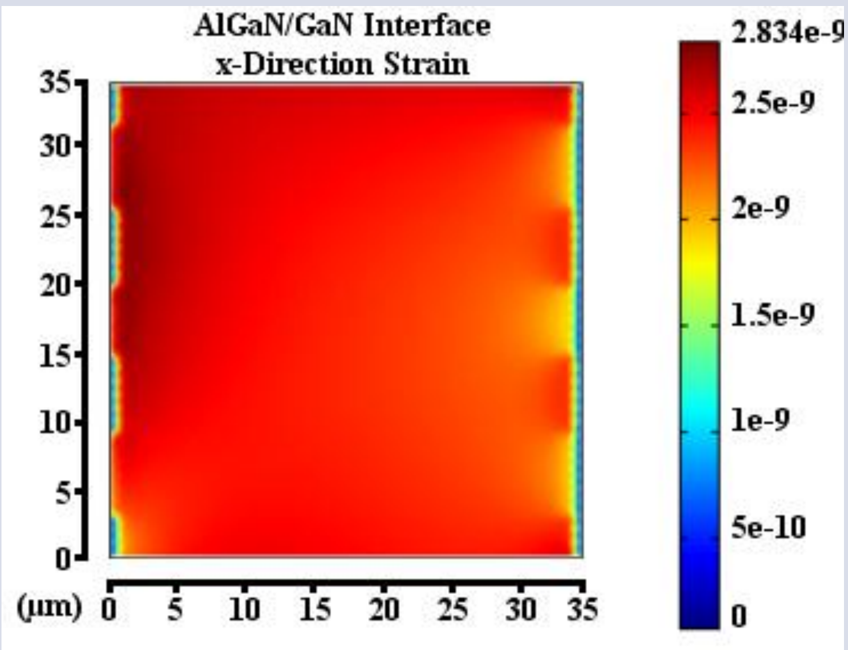
- All static simulations use a 0.1 nN distributed force on the free end.
- Displacement: 66.32 pm
- Spring Constant:
  - Simulated: 1.5 N/m
  - Theoretical: 1.34 N/m
- Extra layers added (Contacts, mesa geometry) will reduce strains at the HFET location.
- *y*-direction strains were found to be an order less than *x*-strains
  - y-strains can be safely ignored

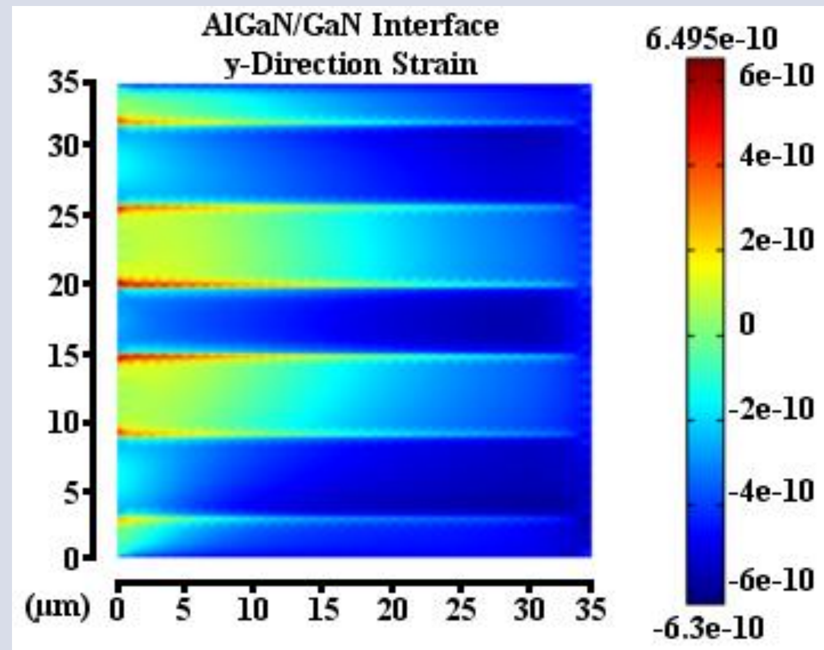


Constraints and force conditions applied to the model

Simulation - Static

- Mapped strains at AlGaN/GaN interface on mesa

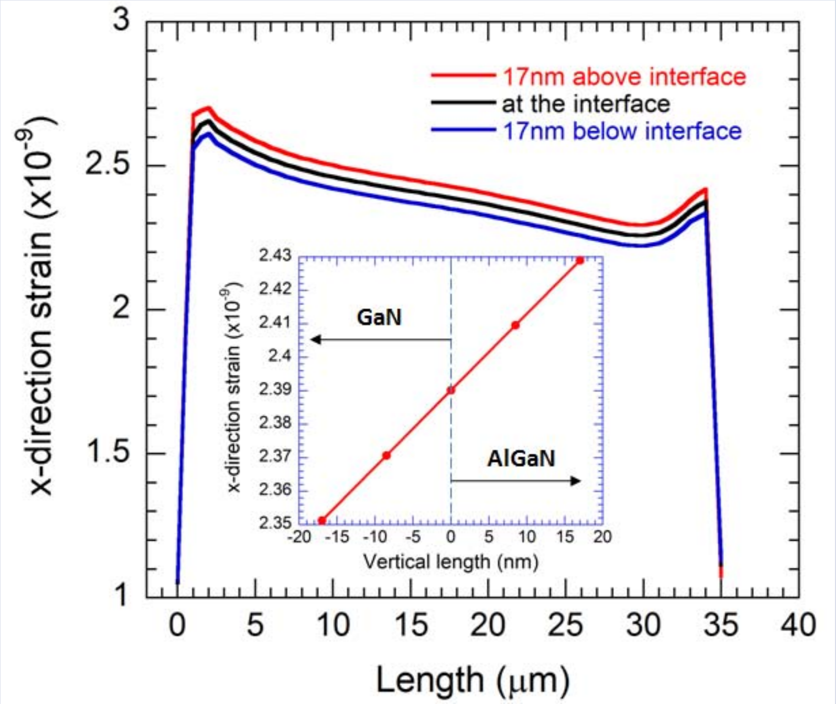




Tip force applied is 0.1 nN

Simulation - Static

- Another important factor is x-strain along the vertical direction.
  - Major strains are in the *x*-direction
  - Bending occurs in the *z*-direction
- Strain varies depending in vertical location
- These strain variations create a polarization profile that will not change abruptly at the interface.



Simulation - Harmonic

- Frequency sweeps were performed using COMSOL simulations and compared to experimental results.
- The Rayleigh damping parameter was used to simulate quality factor (Q)

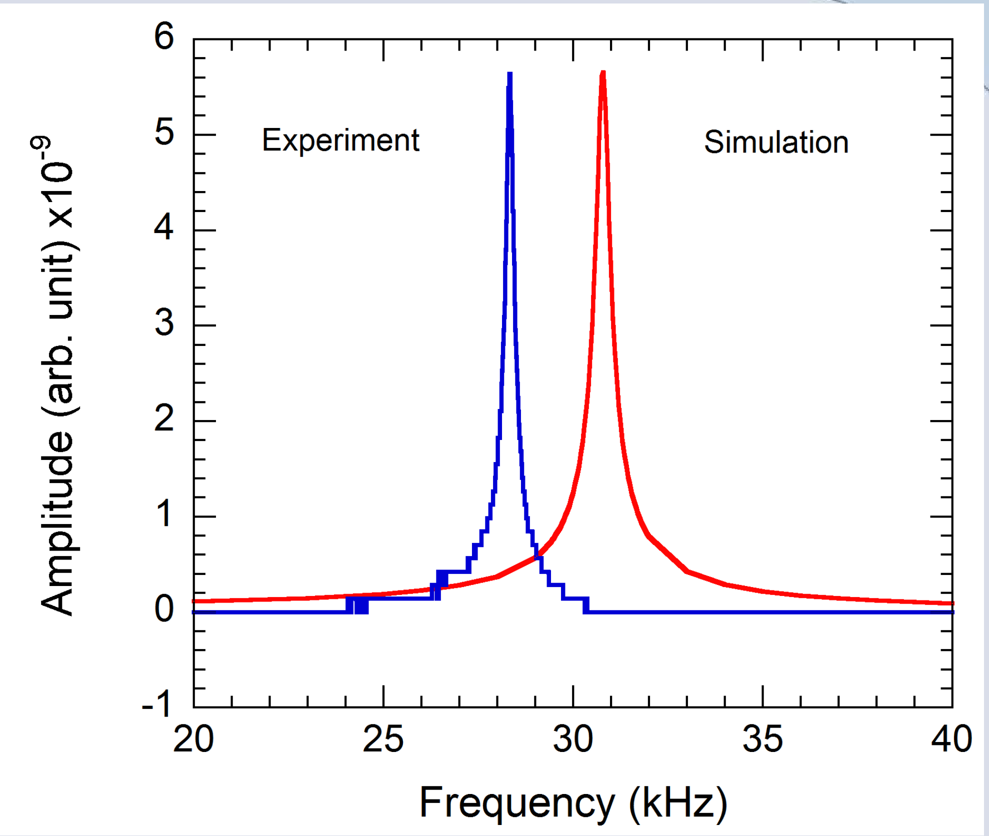
<u>Damping constant:</u>

$$D = \left(\frac{m\omega_0}{Q} \right)$$

<u>Rayleigh damping model:</u>

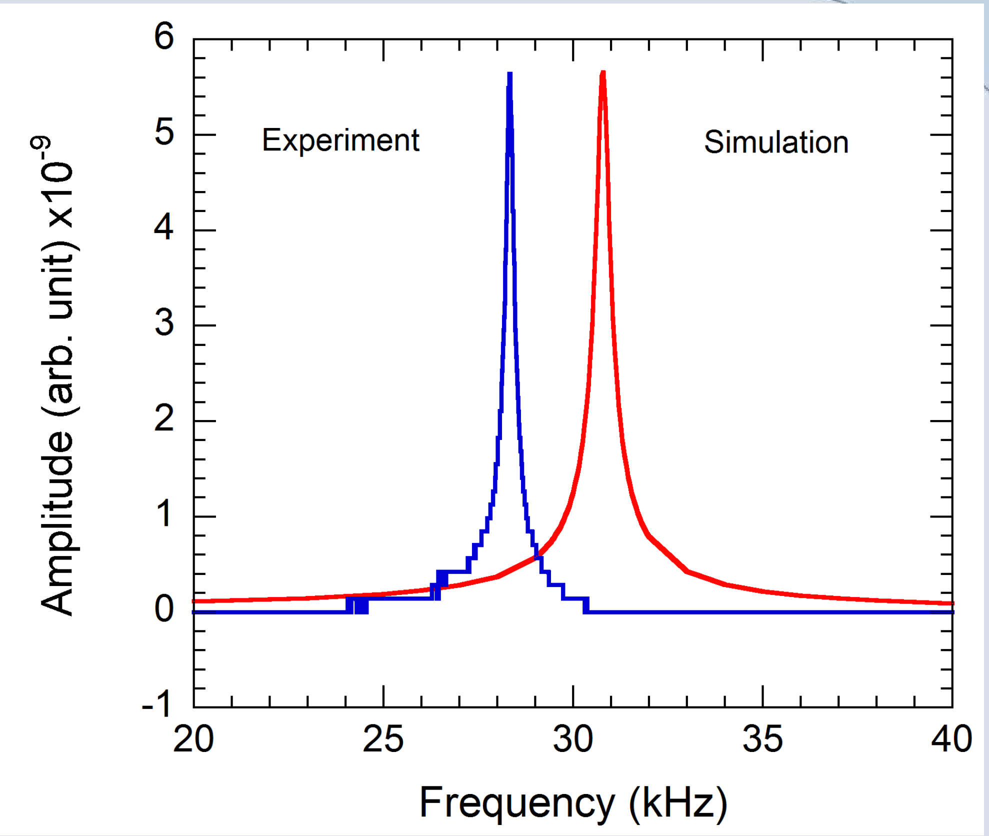
$$D = \alpha m + \beta k$$

$\alpha = 0$ $\beta = 5.94 \times 10^{-8}$



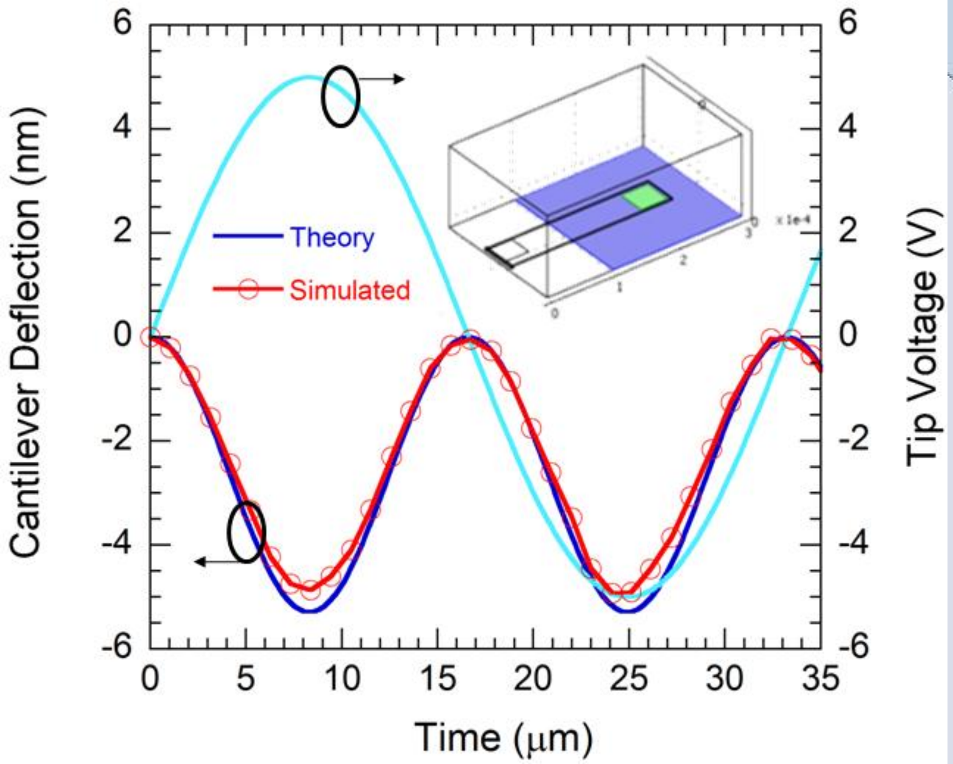
Simulation - Harmonic

- Harmonic analysis yields a quality factor of 50.5
  - lower than experimental value (80)
- The observed frequency shift may be due to over-etch of the microcantilevers during fabrication.



Simulation - Electrostatic

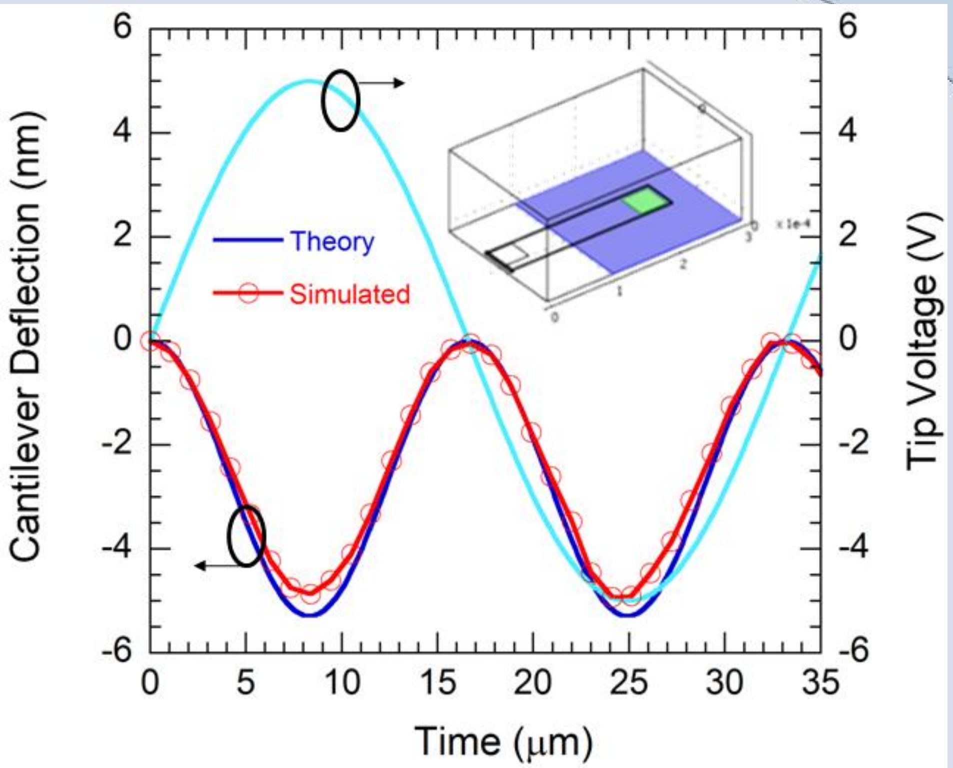
- Transient analysis were performed to observe the deflection given an AC input.
- Because of solve time/hardware constraints, a much simpler model is used.



Simulation - Electrostatic

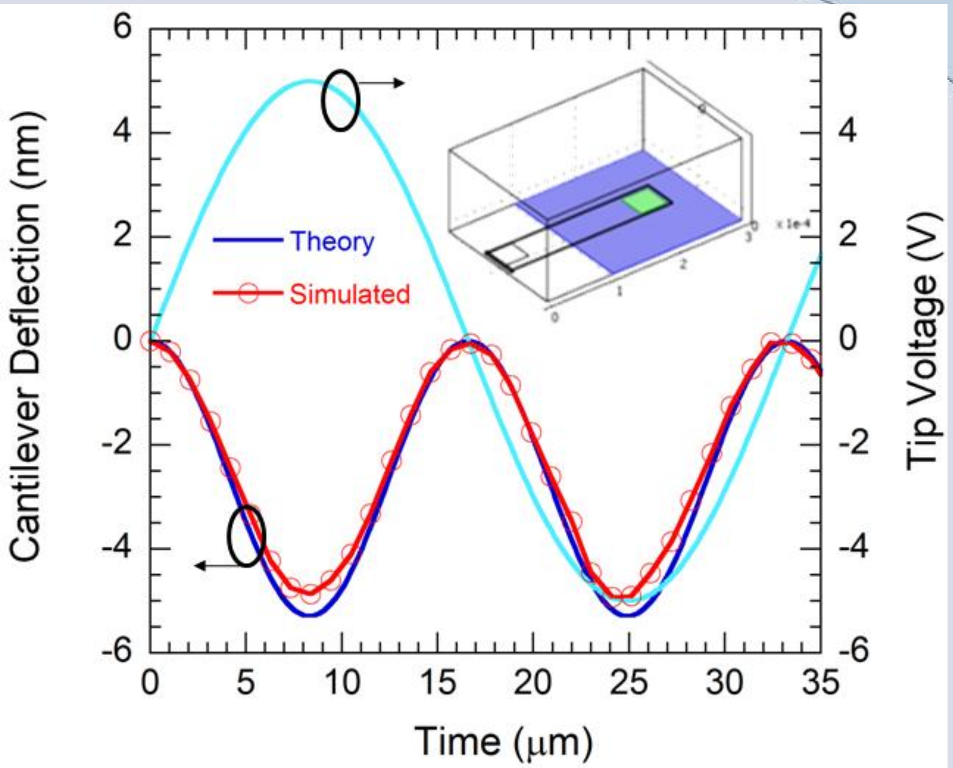
- Oscillation depends on[9]:
  - Quality factor (Q)
  - AC voltage (V_{ac})
  - SWF difference (Δϕ)
  - Spring constant (k)
  - Bias separation (z)
  - Bias area (A)
  - relative permittivity of separating medium (ε)

$$\Delta a = \left(\frac{\varepsilon A}{z^2} \cdot \frac{Q}{k} \cdot V_{ac} \right) \times \Delta\varphi$$



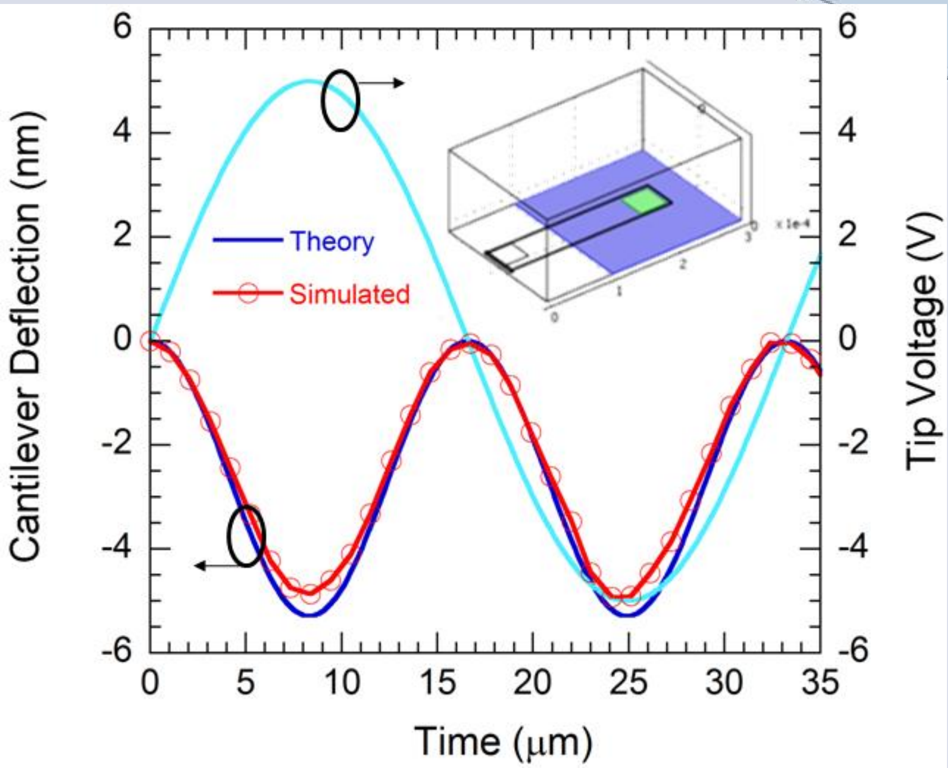
Simulation - Electrostatic

- Theoretical calculation was done using ode45 in MATLAB
- Simulations run in COMSOL 3.5a solved for a DC voltage for each time step.
  - These discrete time steps do not incorporate Q



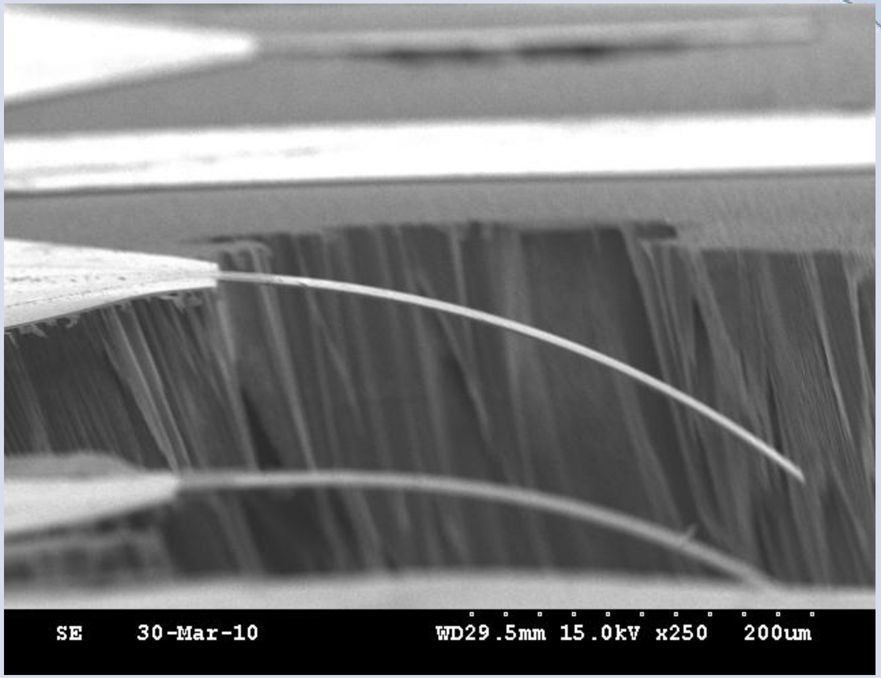
Simulation - Electrostatic

- To handle the discrete solving problem we considered Q=1 when running our theoretical calculations.
- Theoretical model considers two constantly parallel plates
- The slight discrepancy observed demonstrates COMSOL's ability to handle fringing effects and non-uniformity of plate separation.



Conclusion

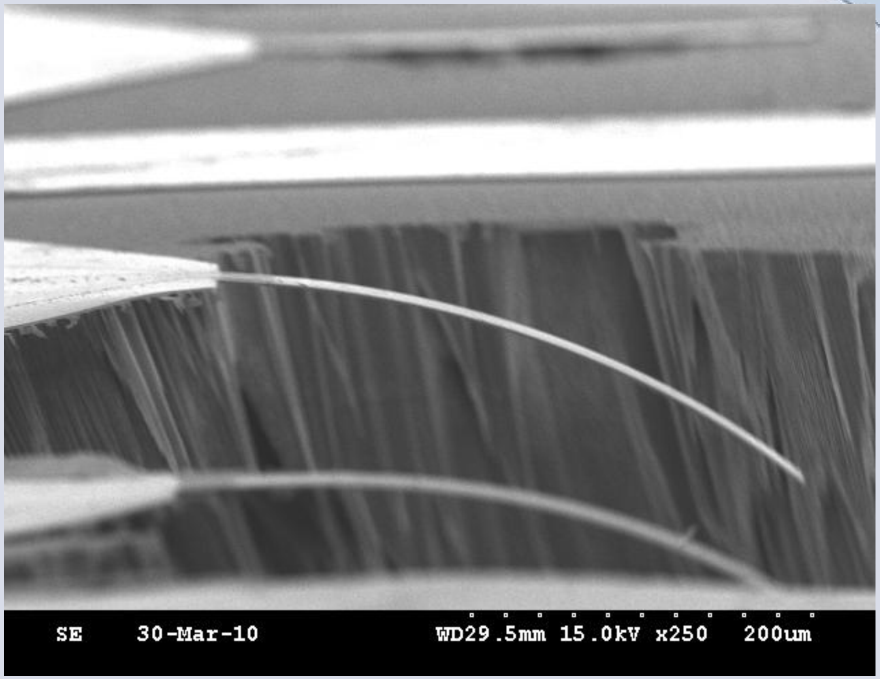
- COMSOL simulations can help us investigate electromechanical parameters of our cantilever sensor.
- The static simulations help us predict strains and the spring constant with greater accuracy than standard theory.
- Simulating the harmonic response we were able to closely match resonant frequency and quality factor.
- COMSOL helps us run more realistic analysis when observing electrostatic properties. We are able to account for fringing field effects and non-uniformity; something standard PDEs cannot perform.



AlGaN/GaN cantilever bent due to residual stress

Future Work

- Investigate effect of vertical strain variations near the 2DEG interface.
- Strain to current relationship simulated and observed experimentally.
- Account for prestress due to thermal mismatch between layers in simulations.
- Improve electrostatic model to account for quality factor enhancement at resonant frequency.
- Alter electrostatic model to no longer solve each time step discreetly.



AlGaN/GaN cantilever bent due to residual stress

Collaboration

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References

1. Z. Hu, Z, T. Thundat, R. J. Warmack, Investigation of adsorption and absorption-induced stresses using microcantilever sensors. *J. Appl. Phys.*, **90**, 427-431 (2001).
2. T. P. Burg1, M. Godin, S. M. Knudsen, W. Shen, G. Carlson, J. S. Foster, K. Babcock, and S. R. Manalis, Weighing of biomolecules, single cells and single nanoparticles in fluid, *Nature*, 446, 1066-1069 (2007).
3. L. A.Pinnaduwage, A. Gehl, D. L. Hedden, G. Muralidharan, T. Thundat, R. T. Lareau, T. Sulchek, L. Manning, B. Rogers, M. Jones, J. D. Adams, A microsensor for trinitrotoluene vapor. *Nature*, **425**, 474 (2003).
4. N. V. Lavrik, M. J. Sepaniak, and P. G. Datskos, Cantilever transducers as a platform for chemical and biological sensors, *Rev. of Scientific Instruments*, **75**, 2229-2253 (2004).
5. K. Tonisch,C. Buchheim, F. Niebelschütz, A. Schober, G. Gobsch, V. Cimalla, O. Ambacher, and R. Goldhahn, Piezoelectric actuation of (GaN/)AlGaN/GaN heterostructures, *J. Appl. Phys.,* **104**, 084516 (2008).
6. T. Zimmermann, M. Neuburger, P. Benkart, F. J. Hernández-Guillén, C. Pietzka, M. Kunze, I. Daumiller, A. Dadgar, A. Krost, and E. Kohn, "Piezoelectric GaN Sensor Structures", *IEEE Electro. Device Lett.*, **27**, 309 (2006)
7. T. Zimmermann et. al., "Piezoelectric GaN Sensor Structures", IEEE Electro. Device Lett. **27**, 309 (2006).
8. O. Ambacher et. al., "Two-dimensional electron gases induced by spontaneous and piezoelectric polarization charges in N- and Ga-face AlGaN/GaN heterostructures", *J. Appl. Phys.*, **85**, 3222 (1999).
9. G. Koley et. al., "Gas sensing using electrostatic force potentiometry," *Appl. Phys. Lett*. **90**, 173105 (2007).