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

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• Fabrication
• Simulation
  – Static
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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

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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.
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.
• Piezoelectric polarization:[8]

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

\( \varepsilon_x, \varepsilon_y, \varepsilon_z = x, y, \text{ and } z\)-direction strains

\( e_{33}, e_{31} = \) piezoelectric constants for Al\(_x\)Ga\(_{1-x}\)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
Simulation - Static

- Mapped strains at AlGaN/GaN interface on mesa

Tip force applied is 0.1 nN

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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)

Damping constant:

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

Rayleigh damping model:

\[ D = \alpha m + \beta k \]

\[ \alpha = 0 \quad \beta = 5.94 \times 10^{-8} \]
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.
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 ($\Delta \phi$)
  - Spring constant (k)
  - Bias separation (z)
  - Bias area (A)
  - Relative permittivity of separating medium ($\varepsilon$)

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


