Piezoresponse Force Microscopy (PFM) on GaN Nanowires
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Growth of nanowires

- Grown by catalytic CVD using Au or Fe catalyst nanoparticles \(^1\)

- \(\text{NH}_3\) gas flow provides N via: \(2\text{Ga} + 2\text{NH}_3 \rightarrow 2\text{GaN} + 3\text{H}_2\)

- Growth time, growth temp, flow rate, flow composition and Ga source/substrate distance influence growth
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Growth of nanowires

• Growth explained by VLS growth mechanism
  - V: Ga, N from vapor adsorb on nanoparticle surface
  - L: Ga, N and Metal liquid alloy forms around initial particle
  - S: Ga, N attain solubility limit and precipitate solid GaN out of solution

- Single crystal wurtzite nanowires (a=0.318nm, c=0.517nm)
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Characterization of nanowires

EDS Spectrum ¹:

HRTEM ¹:

PL Spectrum ¹:

XRD Spectrum ¹:
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AFM Characterization

a) Amplitude
b) Phase
c) Width~200nm,
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Deposition of nanowires on contact grid

• As-grown nanowires dispersed in 2-propanol and sonicated. Suspension deposited on contact grid.

a) Contact grid
b) Optical bright field image of nanowires

• Ti/Al/Pt/Au contact electrodes patterned by photolithography, e-beam evaporation and subsequent lift-off.
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Experimental Set up and Method

- PFM on
  - Unconnected (freestanding) wires
  - Connected wires

- [Image of PFM setup]
- [Image of wire-bonded contacts and tip used during experiment]
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Experimental Set up and Method

- Frequency Band Excitation Method
  - Simultaneous excitation and detection within a band of frequencies rather than at a single frequency
  - Only selected regions of Fourier space contain information of interest
  - Method yields full frequency response at each measured point
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**Piezoresponse investigated by PFM (experimental)**

- Relationship (reduced to linear) between electric field, $E$ and mechanical strain, $\varepsilon$: $\varepsilon_i = d_{ij} E_j$ where $j=1\ldots3$ and $i=1\ldots6$

![Diagram](image)

- Tensile, compressive normal strains $d_{33}$
- Shear strains $d_{15}$

- Single crystal GaN nanowire polarization along [0001] direction (figures c and d) ⁵. Back to slide 10
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Piezoresponse investigated using FLOOPS (simulation)

- Assuming axes in 2D as:

  - Nanowire and polarization, \( P_{sp} \) in [0001] parallel to y axis while lying flat. Applied field from tip, \( E_x \) is to \( P_{sp} \). Refer to: Slide 9 figs.c & d.
  - \( E_y \) is to \( P_{sp} \).

- Normal deformation comes from the piezoresponse of small volume just underneath the tip.

- Assuming constant \( d_{33}, d_{13}, d_{15} \) in vicinity of tip, resultant measured strain in volume given by:

  \[
  \varepsilon(x) = d_{15} \int E_x(x,y) \, dx + d_{13} \int E_y(x,y) \, dy \quad d_{15} = 3.1 \text{pm/V}, \quad d_{15} = -1.7 \text{pm/V} \]
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Piezoresponse investigated using FLOOPS (simulated)

- Unconnected GaN nanowire set up:
  - Wire Thickness = 60nm
  - Surface oxide thickness = 2nm
  - SiO2 thickness (which wire is resting on) = 20nm
  - Grounded substrate

Using coefficient matrix:

\[
\begin{pmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\varepsilon_{xy}
\end{pmatrix} =
\begin{pmatrix}
0 & d_{31} \\
0 & d_{33} \\
d_{15} & 0
\end{pmatrix}
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
\]

Measured strain = \varepsilon_{xx} + \varepsilon_{xy}

*E_x large, E_y small
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Experimental results: Piezoresponse of Unconnected GaN nanowire

- a) Piezoresponse at 8V
- b) Hysteresis curves
- c) 3D image of wire

- Linear piezoresponse from $1 \leq V \leq 8$ tip voltage
Simulation results: Piezoresponse of Unconnected GaN nanowire

- Wire strain on curve determined by taking an average strain \((xx+xy)\) of 7 points in a 4nmx 4nm area directly underneath tip contact
- * No clamping effect for free standing wire,
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Experimental results: Piezoresponse of Connected GaN nanowire

Connected wire (1 side grounded)

a) Piezoresponse at 3V  b) Hysteresis curves  c) 3D image of wire

• Linear piezoresponse from $1 \leq V \leq 3$ tip voltage
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Simulation results: Piezoresponse of Connected GaN nanowire

- Wire strain on curve determined by taking an average strain \((xx)^*\) of 7 points in a 4nmx 4nm area directly underneath tip contact
- * Contact restricts shearing forces, so \(xy\) component is removed due to clamping effect
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Experimental vs Simulated comparison for Unconnected GaN nanowire

- Experimental and Simulated piezoresponse at 8V are 2.5e-3 and 1.14e-3 respectively. Decent agreement between the two.
- For unconnected wire, $E_x$ dominates, $E_y$ is negligible so Shear strain, $d_{15}$ dominates the measured response.
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Experimental vs Simulated comparison for Connected (1 side) GaN nanowire

- Experimental and simulated piezoresponses show same trend. Clamping (displacement=0 at edge) causes shear strain contribution from $E_x$ to be minimized.
- For connected wire, $E_y$ determines strain. Coeff. $d_{13}$ (Poisson’s ratio) determines the measured response.
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Conclusions and Further Work

• Initial 2D strain simulations using coefficients listed for bulk GaN in reasonable agreement with nanowire piezoresponse measured by experiments.

• 3D simulation needed for more accurate comparison.

• Measurement on fully connected (2 sides) GaN nanowires

• Simulation of experimentally measured hysteresis effect.

• Extraction of accurate coefficients specific to GaN nanowires difficult due field superposition and inevitable clamping effect
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References

Back-up Slides

• Slide 21 - Simulation pictures
• Slide 22 – Experiment results showing hysteresis
Unconnected and connected wire simulation pictures
Experimental results: Piezoresponse with Hysteresis

- Unconnected GaN nanowire

a) Piezoresponse at 5V  
b) Hysteresis curves  
c) 3D image of wire

- Hysteresis from +5 ≤ V ≤ 0 tip voltage swing