Vertically Aligned Carbon Nanotubes Embedded in Ceramic Matrices for Hot Electrode Applications

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http://lane.unl.edu
April 12th, 2018
<table>
<thead>
<tr>
<th><strong>Project Title:</strong></th>
<th>Vertically Aligned Carbon Nanotubes Embedded in Ceramic Matrices for Hot Electrode Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Grant Number:</strong></td>
<td>DE-FE0023061</td>
</tr>
<tr>
<td><strong>Project Investigator:</strong></td>
<td>Yongfeng Lu</td>
</tr>
<tr>
<td><strong>Recipient Organization:</strong></td>
<td>University of Nebraska - Lincoln</td>
</tr>
<tr>
<td><strong>Project Period:</strong></td>
<td>10/01/2014 – 09/30/2018</td>
</tr>
</tbody>
</table>
**Primary goal:** Develop carbon nanotubes-ceramic (CNT-C) composite structures in which vertically aligned CNTs (VA-CNTs) are embedded in ceramic matrices for hot electrode applications in magnetohydrodynamics (MHD) power systems.

**CNTs:** $T_m > 1726 \, ^\circ C$
- Oxidation resistance $\sim 700 \, ^\circ C$
- $\sigma = 10^6 - 10^7 \, S/m$
- $K = 200 - 30,000 \, W/(m\cdot K)$

**BN:** $T_m > 2900 \, ^\circ C$
- Oxidation resistance $\sim 1500 \, ^\circ C$
- Insulator
  - $K = 600 - 740 \, W/(m\cdot K)$

**Cu:** $T_m = 1084 \, ^\circ C$
- Oxidation resistance $< 200 \, ^\circ C$
- $\sigma = 59.6 \times 10^6 \, S/m$
- $K = 401 \, W/(m\cdot K)$
Objectives:

1. Super growth of VACNT carpets
2. Fabrication of CNT-BN composite structures
3. Stability and resistance studies of the CNT-BN composite structures
4. Thermionic emissions from the CNT-BN composite structures
## Goal and Objectives

### Milestone of the project

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Milestone</th>
<th>Planned Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Project Management and Planning</td>
<td>Successful completion of the proposed project within the 3-year period.</td>
<td>09/30/2017</td>
</tr>
<tr>
<td>2. Super Growth of Vertically Aligned CNT Carpets</td>
<td>Achieve the growth of VA-CNT carpets on Cu substrates with CNT lengths up to 1 cm.</td>
<td>09/30/2015</td>
</tr>
<tr>
<td>3. Fabrication of CNT-BN Composite Structures</td>
<td>Achieve uniform and dense growth of BN matrices wrapping VA-CNTs.</td>
<td>03/31/2016</td>
</tr>
<tr>
<td>4. Stability and Resistance Studies of the CNT-BN Composite Structures</td>
<td>Determine the stability and resistance of the CNT-BN composite structures</td>
<td>09/30/2016</td>
</tr>
<tr>
<td></td>
<td>Determine the electrical and thermal conductivities of the CNT-BN composite structures.</td>
<td>09/30/2017</td>
</tr>
<tr>
<td>5. Thermionic Emissions from the CNT-BN Composite Structures</td>
<td>Determine the thermionic emission performance of the CNT-BN composite structures.</td>
<td>09/30/2018</td>
</tr>
</tbody>
</table>
1. **Background and Motivations**

2. **Accomplishments**
   1) Improving BN growth using the chemical vapor deposition method
   2) Structural and elemental analysis of grown BN
   3) Fabricating VACNT-BN structure and testing its oxidation stability
   4) Determining the infiltration of BN into VACNT arrays
   5) Tested gas erosion ability of CNT-BN at extreme temperatures
   6) Tested thermal and electrical conductivity of CNT-BN composite structure

3. **Deliverables**

4. **Status and Future Work**

5. **Student Training**
1. Background and Motivations

Soaring energy demand!

Depleting energy resources!

How are we going to satisfy future energy needs?
1. Background and Motivations

<table>
<thead>
<tr>
<th>Method</th>
<th>Efficiency (%)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>33 – 36</td>
<td>Efficiency in Electricity Generation, EURELECTRIC “Preservation of Resources” Working Group’s “Upstream” Sub-Group in collaboration with VGB, 2003</td>
</tr>
<tr>
<td>Coal</td>
<td>39 – 47</td>
<td></td>
</tr>
<tr>
<td>Natural gas</td>
<td>&lt; 39</td>
<td></td>
</tr>
<tr>
<td>MHD</td>
<td>~ 65</td>
<td><a href="http://www.mpoweruk.com/mhd_generator.htm">http://www.mpoweruk.com/mhd_generator.htm</a></td>
</tr>
</tbody>
</table>

U.S. Electricity Generation (2013)

- Natural Gas 27%
- Coal 39%
- Nuclear 19%
- Other renewable 6%
- Hydroelectric 7%
- Liquid petroleum 2%

U.S. Electricity Generation (2016)

- Natural Gas 35%
- Coal 31%
- Nuclear 19%
- Other renewable 6%
- Hydroelectric 7%
- Liquid petroleum 2%
Advantages:
1) Only working fluid is circulated without moving mechanical parts.
2) The ability to reach full power level almost directly.
3) Lower infrastructure cost than conventional generators.
4) A very high efficiency (60% for a closed cycle MHD).

http://en.wikipedia.org/wiki/Magnetohydrodynamic_generator#Generator_efficiency
1. Background and Motivations

**Material Challenges for a MHD Generator**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical conductivity ($\sigma$)</td>
<td>$\sigma &gt; 1$ S/m, flux $\approx 1$ amp/cm$^2$</td>
</tr>
<tr>
<td>Thermal conductivity ($k$)</td>
<td>High heat flux from the combustion fluids at 2400 K</td>
</tr>
<tr>
<td>Thermal stability</td>
<td>Melting point ($T_m$) above 2400 K</td>
</tr>
<tr>
<td>Oxidation resistance</td>
<td>Resistant to an oxygen partial pressure about $10^{-2}$ atm at 2400 K</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>Potassium seeds and aluminosilicate slags</td>
</tr>
<tr>
<td>Erosion resistance</td>
<td>High velocity hot gases and particulates</td>
</tr>
<tr>
<td>Thermionic emission</td>
<td>The anode and cathode should be good acceptor and emitters, respectively.</td>
</tr>
</tbody>
</table>
1. Background and Motivations

<table>
<thead>
<tr>
<th>Property</th>
<th>CNTs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical conductivity ($\sigma$)</td>
<td>$10^6 – 10^7$</td>
</tr>
<tr>
<td>Thermal conductivity ($k$)</td>
<td>200 – 3000</td>
</tr>
<tr>
<td>Thermal stability</td>
<td>$T_m &gt; 1726 , ^\circ C$</td>
</tr>
<tr>
<td>Oxidation resistance</td>
<td>$\sim 700 , ^\circ C$</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>Yes</td>
</tr>
<tr>
<td>Erosion resistance</td>
<td>Yes</td>
</tr>
<tr>
<td>Thermionic emission</td>
<td>Yes</td>
</tr>
</tbody>
</table>

- 1000 $\times$ current density of copper
- 5 $\times$ electrical conductivity of copper
- 15 $\times$ thermal conductivity of copper
- 1/7 density of copper and ½ or Al

3,500 pounds of Cu and 147,000 pounds of Al in a Boeing 747

Y. Won, Y. Gao et al., PNAS, 2013, 110(51), 20426-20430.
1. Background and Motivations

<table>
<thead>
<tr>
<th>Property</th>
<th>BN</th>
<th>C-BN</th>
<th>h-BN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical conductivity ($\sigma$)</td>
<td>Insulating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity ($k$)</td>
<td>600 - 740</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal stability</td>
<td>$T_m = 2973$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxidation resistance</td>
<td>$\sim 1500 , ^\circ C$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Erosion resistance</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermionic emission</td>
<td>N.A.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

http://www.graphene-info.com/3d-white-graphene-could-cool-electronics
1. Background and Motivations

<table>
<thead>
<tr>
<th></th>
<th>Graphene</th>
<th>h-BN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space group</td>
<td>$P_{63}$</td>
<td>$P_{63}$</td>
</tr>
<tr>
<td>Lattice constant, $a$ (Å)</td>
<td>2.46</td>
<td>2.50</td>
</tr>
<tr>
<td>Lattice constant, $c$ (Å)</td>
<td>6.70</td>
<td>6.66</td>
</tr>
<tr>
<td>Thermal expansion coefficient ($10^{-6} °C^{-1}$)</td>
<td>-1.5 $\parallel$, 25 $\perp$</td>
<td>-2.7 $\parallel$, 38 $\perp$</td>
</tr>
</tbody>
</table>

Within the basal planes ($\parallel$) and perpendicular to them ($\perp$)
### 1. Background and Motivations

**Proposed Solution: CNT-BN Composite Structures**

<table>
<thead>
<tr>
<th>Property</th>
<th>BN</th>
<th>CNTs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point (°C / K)</td>
<td>2973 / 3246</td>
<td>&gt; 1726 / 2000</td>
</tr>
<tr>
<td>Chemical inertness</td>
<td>Inert to acids but soluble in alkaline molten salts and nitrides</td>
<td>Yes</td>
</tr>
<tr>
<td>Oxidation resistance in open air (°C / K)</td>
<td>1500 / 1773</td>
<td>&lt; 700 / 973</td>
</tr>
<tr>
<td>Electrochemical passiveness</td>
<td>Yes. Used as electrode.</td>
<td>Yes.</td>
</tr>
<tr>
<td>Electrical conductivity (S/m)</td>
<td>Insulating</td>
<td>10^6 - 10^7</td>
</tr>
<tr>
<td>Thermal conductivity [W/(m·K)]</td>
<td>600 - 740</td>
<td>Up to 3000</td>
</tr>
</tbody>
</table>

- **VACNTs:** Electrical and thermal conductive channels.
- **BN:** Protective layer shielding CNTs from erosive and corrosive environments.
A review of previous research

1) Obtained patterned VACNTs

2) Built a CVD system for BN growth

3) Obtained various VACNT-Ceramic (Si, GaN, BN) structure

4) Tested anti-oxidation ability of CNT-Ceramic (Si, GaN, BN)
2. Accomplishments

1) Improving BN growth using the chemical vapor deposition method
2) Structural and compositional analysis of grown BN
3) Oxidation stability of grown BN
4) Infiltration of BN into VACNT arrays
5) Fabricating VACNT-BN infiltrated structure and testing its oxidation stability
6) Gas erosion resistance of CNT-BN at extreme temperatures
7) Thermal and electrical conductivity of CNT-BN composite structure
2. Accomplishments
- Improving BN using thermal CVD method

**Improving thermal CVD system for BN growth**

BF₃ and NH₃ are separately fed into the hot zone to prevent undesired reaction at low temperature.
2. Accomplishments
- Improving BN using thermal CVD method

**Improving thermal CVD system for BN growth**

<table>
<thead>
<tr>
<th>Growth Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precursor</td>
<td>NH₃(100 sccm) BF₃ (75 sccm)</td>
</tr>
<tr>
<td>Temperature</td>
<td>1000-1100 °C</td>
</tr>
<tr>
<td>Chamber pressure</td>
<td>2-3 Torr</td>
</tr>
<tr>
<td>Growth time</td>
<td>30-180 min</td>
</tr>
<tr>
<td>Substrate</td>
<td>SiO₂/Si</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>N₂ Flushing</th>
<th>Heating</th>
<th>Growth</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT</td>
<td>60</td>
<td>1100 °C</td>
<td>RT</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>N₂ (Torr)</th>
<th>NH₃ (sccm)</th>
<th>BF₃ (sccm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>10</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;60</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
2. Accomplishments

1) Improving BN growth using the chemical vapor deposition method

2) **Structural and compositional analysis of grown BN**

3) Oxidation stability of grown BN

4) Infiltration of BN into VACNT arrays

5) Fabricating VACNT-BN infiltrated structure and testing its oxidation stability

6) Gas erosion resistance of CNT-BN at extreme temperatures

7) Thermal and electrical conductivity of CNT-BN composite structure
2. Accomplishments

- Structural and compositional analysis of grown BN

**Structural analysis: Thin BN film on SiO$_2$/Si (Optical images & AFM)**

10 min

20 min

30 min
2. Accomplishments
- Structural and compositional analysis of grown BN

Composition analysis: Thin BN on SiO₂/Si

![SEM image](image1)

10 min

![SEM image](image2)

30 min

![EDS](image3)

![Raman spectrum](image4)
2. Accomplishments
- Structural and compositional analysis of grown BN

**Structural analysis: Thick BN film on SiO$_2$/Si**

3 hr growth

- BN (top) (~9.5 μm)
- BN (bottom) (~2.3 μm)
- SiO$_2$/Si substrate

---

500 nm

---

500 nm

---

500 nm
2. Accomplishments
- Structural and compositional analysis of grown BN

**Structural analysis: Thick BN film on SiO₂/Si (HRTEM)**
2. Accomplishments
- Structural and compositional analysis of grown BN

**Composition analysis: Thick BN film on SiO$_2$/Si (Raman mapping)**

![Raman mapping of Composition analysis: Thick BN film on SiO$_2$/Si](image-url)
2. Accomplishments
- Structural and compositional analysis of grown BN

Composition analysis: Thick BN film on SiO$_2$/Si (Polarized Raman)
2. Accomplishments
- Structural and compositional analysis of grown BN

Composition analysis: Thick BN film on SiO₂/Si (Polarized CARS)
2. Accomplishments

1) Improving BN growth using the chemical vapor deposition method
2) Structural and compositional analysis of grown BN
3) Oxidation stability of grown BN
4) Infiltration of BN into VACNT arrays
5) Fabricating VACNT-BN infiltrated structure and testing its oxidation stability
6) Gas erosion resistance of CNT-BN at extreme temperatures
7) Thermal and electrical conductivity of CNT-BN composite structure
2. Accomplishments
- Oxidation stability of grown BN

Oxidation stability of as-grown thick h-BN (in air)

Scale bars: 100 um
2. Accomplishments
- Oxidation stability of grown BN

Oxidation stability of as-grown thick h-BN (in air)

Slight decrease in thickness
2. Accomplishments
- Oxidation stability of grown BN

Oxidation stability of as-grown h-BN (in air)
2. Accomplishments

1) Improving BN growth using the chemical vapor deposition method
2) Structural and compositional analysis of grown BN
3) Oxidation stability of grown BN
4) Infiltration of BN into VACNT arrays
5) Fabricating VACNT-BN infiltrated structure and testing its oxidation stability
6) Gas erosion resistance of CNT-BN at extreme temperatures
7) Thermal and electrical conductivity of CNT-BN composite structure
2. Accomplishments
- Infiltration of BN into VACNT array

Infiltration of BN into VACNT array

CNTs

\[
\text{SiO}_2/\text{Si}
\]

\[\xrightarrow{\text{Thermal CVD}}\]

\[1100 \, ^\circ\text{C}\]

CNT-BN

\[
\text{SiO}_2/\text{Si}
\]
2. Accomplishments
- Infiltration of BN into VACNT array

Infiltration of BN into VACNT arrays with different height
2. Accomplishments
   - Infiltration of BN into VACNT array

Infiltration of BN into long VACNT arrays
2. Accomplishments
- Infiltration of BN into VACNT array

Infiltration of BN into long VACNT arrays
2. Accomplishments
- Infiltration of BN into VACNT array

Infiltration of BN into VACNT arrays (EDS mapping)
2. Accomplishments

- Infiltration of BN into VACNT array

**Infiltration of BN into VACNT arrays (EELS mapping)**
2. Accomplishments

1) Improving BN growth using the chemical vapor deposition method
2) Structural and compositional analysis of grown BN
3) Oxidation stability of grown BN
4) Infiltration of BN into VACNT arrays
5) Fabricating VACNT-BN infiltrated structure and testing its oxidation stability
6) Gas erosion resistance of CNT-BN at extreme temperatures
7) Thermal and electrical conductivity of CNT-BN composite structure
2. Accomplishments
- Fabricating VACNT-BN infiltrated structure

Thin VACNT-BN film (Cross-sectional SEM)
2. Accomplishments
- Fabricating VACNT-BN infiltrated structure

**Thick VACNT-BN film (Cross-sectional SEM)**
2. Accomplishments
- Fabricating VACNT-BN infiltrated structure

Fabricating milimeter long VACNT-BN (~2mm)
2. Accomplishments
- Fabricating VACNT-BN infiltrated structure

Thermal stability of VACNT-BN ($O_2$ 100 mTorr)

1200 °C
2. Accomplishments
- Fabricating VACNT-BN infiltrated structure

**Thermal stability of VACNT-BN (O\textsubscript{2} 100 mTorr)**

- **Raman shift (cm\textsuperscript{-1})**
  - 1400 °C
  - 1300 °C
  - 1200 °C
  - 1100 °C
  - Pristine

- **Peak position (cm\textsuperscript{-1})**
- **FWHM (cm\textsuperscript{-1})**

- **Oxidation temperature (°C)**
2. Accomplishments

1) Improving BN growth using the chemical vapor deposition method
2) Structural and compositional analysis of grown BN
3) Oxidation stability of grown BN
4) Infiltration of BN into VACNT arrays
5) Fabricating VACNT-BN infiltrated structure and testing its oxidation stability
6) **Gas erosion resistance of CNT-BN at extreme temperatures**
7) Thermal and electrical conductivity of CNT-BN composite structure
2. Accomplishments
- Gas erosion ability of CNT-BN at extreme temperatures

Gas erosion ability of CNT-BN at extreme temperatures

[Graph and image showing the gas erosion process and the changes over time]
2. Accomplishments

1) Improving BN growth using the chemical vapor deposition method
2) Structural and compositional analysis of grown BN
3) Oxidation stability of grown BN
4) Infiltration of BN into VACNT arrays
5) Fabricating VACNT-BN infiltrated structure and testing its oxidation stability
6) Gas erosion resistance of CNT-BN at extreme temperatures
7) Thermal and electrical conductivity of CNT-BN composite structure
2. Accomplishments
- Thermal conductivity of VACNT-ceramic infiltrated structure

Thermal conductivity the VACNT-BN infiltrated structure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>h-BN</th>
<th>G-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_p$ (cm$^{-1}$/mW)</td>
<td>3.57</td>
<td>4.24</td>
</tr>
<tr>
<td>$\chi_T$ (cm$^{-1}$/K)</td>
<td>0.0094</td>
<td>0.014</td>
</tr>
<tr>
<td>$\Delta \bar{T}$ (K/mW)</td>
<td>379.79</td>
<td>302.86</td>
</tr>
<tr>
<td>$k$ [W/(m·K)]</td>
<td>438.83</td>
<td>550.31</td>
</tr>
</tbody>
</table>
2. Accomplishments
- Electrical conductivity of VACNT-ceramic infiltrated structure

Room-temperature electrical conductivity the VACNT-BN infiltrated structure

- $15 \times 2 \times 10 \text{ um}^3$ (L W H)

A CNT-BN device is attached to gold electrodes.

![Graph showing current (mA) and voltage (V) with R=673.58 \Omega and \sigma=1060.43 \text{ S/m}](image)
2. Accomplishments
- Summary

1) Improved BN growth method via thermal CVD
2) Obtained good quality BN films on SiO$_2$/Si
3) Obtained infiltrated VACNT-BN structures (both films and cubic patterns)
4) Tested VACNT-BN structures with good oxidation stability (1400 °C)
5) Tested VACNT-BN structures with good thermal conductivity and excellent electrical conductivity
6) Tested VACNT-BN structures with good hot gas erosion resistance (126 min)
3. Deliverables

1) BN films

2) VACNT, VACNT-BN infiltrated composite structures

3) VACNT-BN device
### 4. Future work
- Status of the project

<table>
<thead>
<tr>
<th>Goals</th>
<th>Milestone</th>
<th>Planned Completion Date</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super Growth of Vertically Aligned Carbon Nanotube (VACNT) Carpets</td>
<td>Achieving the growth of VACNT carpets on Cu substrates with CNT lengths up to 1 cm.</td>
<td>09/30/15</td>
<td>Obtaining millimeter long VA-CNT carpets (up to 4 mm)</td>
</tr>
<tr>
<td>Fabrication of CNT-Boron-Nitride (CNT-BN) Composite Structures</td>
<td>Achieving uniform and dense growth of BN matrices wrapping VA-CNTs.</td>
<td>03/31/16</td>
<td>Obtaining CNT-BN infiltrated composite structures</td>
</tr>
<tr>
<td>Stability and Resistance Studies of the CNT-BN Composite Structures</td>
<td>Determining the stability and resistance of the CNT-BN composite structures.</td>
<td>09/30/17</td>
<td>Determined the high-temperature stability/oxidation resistance (1400 °C) of CNT-BN infiltrated composite structures</td>
</tr>
<tr>
<td>Thermionic Emissions from the CNT-BN Composite Structures</td>
<td>Determining the electrical and thermal conductivities of the CNT-BN composite structures.</td>
<td>09/30/18</td>
<td>Determined thermal and electrical conductivity; testing thermionic emission of CNT-BN infiltrated composite structures;</td>
</tr>
</tbody>
</table>
## 4. Future work
- Planned Activities in the Next-Phase

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Methods</th>
<th>Millstones</th>
<th>Planned Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical stability of CNT-BN composite structures</td>
<td>Chemical corrosion</td>
<td>Achieving CNT-Si$_3$N$_4$ infiltrated composite structures</td>
<td>09/30/18</td>
</tr>
<tr>
<td>High temperature electrical conductivity studies of the CNT-BN composite structures</td>
<td>Home-made electrical conductivity measurement system (77 K to 1800 K)</td>
<td>Electrical conductivity: &gt; 1 S/m; thermal conductivity: &gt; 50 W/m·K</td>
<td>09/30/18</td>
</tr>
<tr>
<td>Thermionic emission current measurement of the CNT-BN composite structures</td>
<td>Acetylene torch with tungsten electrodes in air.</td>
<td>CNT-BN composite structures can be used as good emitters</td>
<td>09/30/18</td>
</tr>
</tbody>
</table>
## 5. Student Training

<table>
<thead>
<tr>
<th>Student</th>
<th>Program</th>
<th>Training</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qiming Zou</td>
<td>PhD student at UNL</td>
<td>Under the support of this project, he was trained with all required experiments and data analysis related to fabricating and characterizing patterned VACNTs, BN, GaN, VACNT-BN, VACNT-Al$_2$O$_3$, VACNT-GaN, VACNT-GaN-Si composite structures.</td>
</tr>
</tbody>
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We would like to express our heartfelt thankfulness for the Department of Energy and National Energy Technology Laboratory (Grant Number: DE-FE0023061) for the generous financial support.
Thank you!