One-Dimensional Nanomaterials for Energy and Electronics Applications

Latika Menon
Our laboratory specializes in the synthesis of diverse nanomaterials for a variety of applications.

Key attributes of our research
• Low-cost synthesis approaches amenable to quick industry uptake
• Rapid and scalable production process
• Use earth-abundant starting materials and adhere to sustainability standards
Template-based fabrication of nanowire arrays

- Low-cost electrochemical process for deposition of metals, alloys – Au, Ag, Fe, Co, Ni, FeCo
- Good control over size, wire spacing and stoichiometry
- Wires are polycrystalline
### Possible Applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Key advantages afforded by metal/alloy nanowires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic/Spintronic Applications</td>
<td>Low power storage and processing</td>
</tr>
<tr>
<td>Optoelectronic devices</td>
<td>Multifunctional properties, Enhanced optical absorption, Ability to tune absorption properties,</td>
</tr>
<tr>
<td>Sensors/Biological tags</td>
<td>Large surface area, Easy attachment to surfaces via thiol-radicals/Au atoms</td>
</tr>
<tr>
<td>Nanobiodevices for neuronal recording/stimulation (eg., brain machine implants)</td>
<td>High spatial and temporal resolution, easy to functionalize, Small form factor for in vivo applications</td>
</tr>
</tbody>
</table>
Metal-dielectric composite structures

- Au/Ag nanowires embedded in porous alumina

- Tune material properties for increased absorption in specific wavelengths
- Application in solar concentrators, negative refraction materials
Au nanowire arrays for neuronal recording applications
GaN Nanowires
We produce GaN nanowires in controlled morphologies

- Low cost, scalable chemical vapor deposition process
- Controlled wire growth – size, polarity, orientation
- Morphological control is achieved easily by adjusting fabrication parameters
GaN nanowires have wide applications in optoelectronics

<table>
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<th>Applications</th>
<th>Key advantages afforded by GaN nanowires</th>
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</table>
| UV Emitters for optical communications      | Low-cost fabrication route
Radiation-hard, high temperature operation, high carrier mobility, high speed switching |
| UV LED                                      | Low amount of material requirement, ability to tune emission wavelength       |
| p-n junction solar cells                    | Ability to control effective surface area                                      |
| UV sensors                                  | High surface area                                                             |
Epitaxial GaN Nanowire networks

Epitaxial GaN Nanowire Network following the hexagonal symmetry of the sapphire substrate

Crystal structure – cubic ZnS
Our lab has extensive device fabrication expertise

Single GaN Nanowire released on electrodes fabricated using FIBL

Epitaxial GaN Nanowires integrated with electrodes fabricated using EBL
Electrical measurements on epitaxial GaN nanowires

- High current carrying capacity
- Transistor characteristics indicate n-type carriers

I-V behavior

Transistor characteristics as a function of gate voltage
Titania Nanotubes
We produce titania nanotubes in different forms:

- Short Nanotubes
- Ultra High Aspect Ratio Nanotubes
- Quasi-periodic Arrays
- Free-standing flakes

Images show various forms of titania nanotubes, including short nanotubes, ultra high aspect ratio nanotubes, quasi-periodic arrays, and free-standing flakes.
Our titania nanotubes – with or without modification - are amenable to diverse applications

<table>
<thead>
<tr>
<th>Applications</th>
<th>Key advantages afforded by titania nanotubes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Filtration and Separation</strong>¹</td>
<td>Low-cost, non-fouling, high-temperature robust and chemically stable membranes offering clean separation at high flux rate</td>
</tr>
<tr>
<td>Desalination</td>
<td>Lower cost, long lifetime membranes</td>
</tr>
<tr>
<td>Batteries</td>
<td>Ultra-fast recharging</td>
</tr>
<tr>
<td>Solar Cells</td>
<td>Ultra-low-cost, integrated photovoltaic and flexible solar cells</td>
</tr>
<tr>
<td>Photodetectors</td>
<td>Ultra-low-cost, Robust, high responsivity detectors for flame detection, XRF devices, communications</td>
</tr>
<tr>
<td>Catalysts</td>
<td>Robust support material for catalytic and photocatalytic applications in hydrogen generation, automobile exhaust and fuel cell applications</td>
</tr>
<tr>
<td>Clinical Applications</td>
<td>Biocompatible, anti-microbial materials with high porosity for drug delivery, stents and implants</td>
</tr>
</tbody>
</table>

¹This application is currently in the R&D stage at Menon Laboratories, Inc.
We are developing ultra-low-cost solar cells based on titania nanotubes

Dye-Sensitized Solar Cell
- Invented in 1991
- Anatase titania nanoparticle anodes
- Dye absorber for solar harvesting
- Liquid electrolyte hole generator

Measured efficiency \( \sim 10\% \)

Electron conductor: TiO\(_2\) nanotubes
Back contact: Ti, TCO
Top contact: Transparent Conducting Oxide
Absorber: Fe\(_2\)O\(_3\) or Cu\(_2\)O
Electrolyte

\(^1\)Solar cells containing metal oxides, E. Panaitescu, C. Richter and L. Menon, PCT/US2014/016027
We have a novel chemical method for the uniform coating of iron oxide nanoparticles.

Iron oxide nanoparticle coated nanotubes

Improved absorption in visible region
We are developing ultra-low-cost solar cells based on titania nanotubes

**Target efficiency** ~ 5%

**Target applications**
- Building integrated photovoltaics
- Wearable devices
- Smart labels
We are developing ultra-low-cost photodetectors based on titania nanotubes

<table>
<thead>
<tr>
<th>Photodetector Type</th>
<th>Technology Maturity</th>
<th>Thermal Stability</th>
<th>Response time</th>
<th>Responsivity</th>
<th>UV/Dark Ratio</th>
<th>Visible-Blind</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT (Hamamatsu)</td>
<td>High</td>
<td></td>
<td>&lt; 200ms</td>
<td>0.1-0.2A/W</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Silicon (with filters)</td>
<td>High</td>
<td>600 K</td>
<td>&lt;1ns</td>
<td>0.2A/W</td>
<td>NA</td>
<td>No</td>
</tr>
<tr>
<td>Silicon Carbide</td>
<td>R&amp;D stage</td>
<td>973 K</td>
<td></td>
<td>58.6mA/W</td>
<td>10</td>
<td>Yes</td>
</tr>
<tr>
<td>Titania Nanotube</td>
<td>Early R&amp;D</td>
<td>&gt;1000 K</td>
<td>0.5s</td>
<td>13A/W</td>
<td>$10^3$</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Titania nanotube is a robust, high-surface area support material for catalysis

- 9% water-splitting efficiency
- 75% CO to CO$_2$ conversion efficiency

Au-decorated nanotubes
Menon Laboratories, Inc.
We specialize in the production of titania nanotube powders

Titania nanotube powders

- Patented low-cost, scalable manufacturing process\(^1\)
- Enhanced active area (~3x typical nanoparticles and ~10\(^4\)x thin films)
- High-temperature robustness (> 1000°C)
- Stable across full pH range
- Titania is anti-microbial and biocompatible

\(^1\)Titania nanotubes prepared by anodization in chloride-containing electrolytes, C. Richter, R. Willey and L. Menon, #8790502, Licensed to Menon Laboratories, Inc.
Key Opportunity

Problems

- Pressing need to treat “produced water”
- Current solutions (chemical treatment, deep well injection) do not effectively clean the water
- Environmental regulations are becoming more stringent

Market Size

- **21B bbl/yr** produced water generated
- **900,000** wells in US
  - **35000** new wells/yr
- **$0.01-$5/bbl** treatment cost

CAGR: ~10%

Membrane filtration offers a one-step clean separation solution but generally it is not cost-competitive
Menon Labs is developing a viable membrane-based filtration solution for cost-competitive, on-site treatment of produced water

- Proprietary solution\(^1,2\) with potential to compete cost-wise with current practices
  - **Low capital cost** because of low-cost, abundant starting materials and inexpensive, scalable production process at all stages (50% less than any other ceramic material)
  - **Low operating expenses** because of high flow rates (>1000 LMH) at low transmembrane pressure (<1 bar)

\(^1\)“Filtering Article Containing Titania Nanotubes”, Eugen Panaitescu and Latika Menon, PCT/US2014/014631
\(^2\)Titania nanotubes prepared by anodization in chloride-containing electrolytes, C. Richter, R. Willey and L. Menon, #8790502
Current Status of R&D

Prototype membranes
• Pressed pellets (2.5 cm diameter, < 1mm thickness)

Filtration setup
• Sterlitech stirring filtration cell (simulated cross-flow) with 3.5 cm² filtration area, 73 PSI max. pressure, 10 ml total capacity (~2 gallons/24 h of running)

Key results
• Demonstrated separation of oil from water from various mixtures and emulsions
• High flow rates (reaching 1000LMH for DI water and 500LMH for oil-water)
• No evidence of fouling found in flow rate evolution studies and microstructural characterization
Path to commercialization

Value Chain

**Materials**
- Titania nanotubes

**Components**
- Ceramic filtration membranes

**Filtration systems**
- Complete filtration solutions

**Produced water treatment solutions**
- Oil field services

**End users**
- Oil and gas companies

Current

Next Steps

- Scale-up Powder production
- Scale-up to industry-standard cylindrical membranes
- Scale-up to industry-standard cross-flow filtration setup

Final solution

Pilot scale setup for on-site applications
Advanced Nanomaterials Lab, Northeastern University

Highlights
- Over 5M in funding to date
- Graduated 6PhDs and 4MS
- Over 80 papers in the area of materials
- Extensive mentoring and outreach activities

Research Funding
- NSF (CAREER, DMR, ECCS, I-CORPS)
- Airforce, Army, ONR
- Menon Laboratories, Inc.

Menon Laboratories, Inc.

Highlights
- Incorporated in 2013
- Clean Tech Open Semifinalist 2014; Top 7 companies nominated for Sustainability Prize in NE regional finals

R&D Funding
- Mass CEC
- Major Oil and Gas company