Novel Approach to Advanced Direct Methanol Fuel Cell Anode Catalysts

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National Renewable Energy Laboratory

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Overview

Timeline

Start: July 2009
End: September 2011
% complete: ≈ 40%

Budget

<table>
<thead>
<tr>
<th>DOE Cost Share</th>
<th>Contractor Cost Share</th>
<th>TOTAL</th>
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<tbody>
<tr>
<td>$2.4M</td>
<td>$69,714</td>
<td>$2.47M*</td>
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<tr>
<td>97%</td>
<td>3%</td>
<td>100%</td>
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</table>

DOE Budget ($K)

<table>
<thead>
<tr>
<th></th>
<th>FY 2009</th>
<th>FY 2010</th>
<th>FY 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>610</td>
<td>950</td>
<td>840</td>
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Barriers

<table>
<thead>
<tr>
<th>Barrier</th>
<th>2010 Target (consumer electronics)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Durability</td>
<td>5000 h</td>
</tr>
<tr>
<td>B: Cost</td>
<td>$3/W</td>
</tr>
<tr>
<td>C. Performance</td>
<td>100 W/L, 100 W/kg</td>
</tr>
</tbody>
</table>

Partners [date under contract]

Colorado School of Mines (CSM) [9/2009]
Jet Propulsion Laboratory (JPL) [12/2009]
MTI MicroFuel Cells (MTI) [N/A]
BASF Fuel Cells (BASF) [N/A]

Kickoff meeting 12/10/2009 at NREL.
**DOE Objective:**
Develop and demonstrate direct methanol fuel cell (DMFC) anode catalyst systems that meet or exceed DOE’s 2010 targets for consumer electronics application.

**Project Goal:**
Improve the catalytic activity and durability of the PtRu for the methanol oxidation reaction (MOR) via optimized catalyst-support interactions.

PtRu on highly oriented pyrolytic graphite (HOPG)

Similar approach for ORR catalysis advantageous for both DMFC and hydrogen fuel cells.
Relevance – Background Data

Performance
Methanol oxidation reaction (MOR) on the anode limits the performance of DMFCs. Hence, focus on improving MOR catalytic activity on the anode.

Previous results for Pt/N-doped HOPG showed 52X higher in mass activity for MOR compared to Pt/undoped-HOPG.

Durability:
Expect the unique stabilization of Pt nanocatalyst observed in the Pt/N-doped HOPG system will translate to the PtRu system and improve DMFC’s durability.

N-doping improved durability of system with minimal aggregation/coarsening of particles.

Cost:
To reduce cost, catalyst activity must be increased by ca. 10X of current state of the art (SOA) system with lower catalyst loading.

Translating the enhanced mass activity for MOR to PtRu can help reduce cost.

Density functional theory calculations predict tethering of catalyst clusters on carbon next to substitutionally implanted nitrogen.
## Approach – AOP Milestones

<table>
<thead>
<tr>
<th>FY09 Milestones</th>
<th>FY10 Milestones</th>
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</table>
| **1** | Perform sputter deposition of PtRu on HOPG surface to establish optimal deposition parameters.  
– can control PtRu phase and composition with power and pressure |
| **2** | Develop a processing system for nitrogen doping of applicable carbon materials.  
– built a system for ion implantation of carbon powders and PtRu deposition |
| **3** | Perform 5 cm² fuel cell testing of MEAs fabricated with novel catalysts with highest performance.  
– initiated benchmarking with commercial catalyst materials |

<table>
<thead>
<tr>
<th><strong>FY09 Milestones</strong></th>
<th><strong>FY10 Milestones</strong></th>
</tr>
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<tbody>
<tr>
<td><strong>1</strong></td>
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</table>
| Establish the optimal nitrogen doping level on a model HOPG substrate for DMFC catalysis.  
– established that 45 seconds implantation of N on HOPG is optimal |
| **2** |
| Conduct preliminary combinatorial electrochemical evaluation of prospective materials and refine the analytical methods for combinatorial library.  
– extended until 04/10 due to delayed in JPL funding |
| **3** |
| **FY10 Milestones** |
| **1** | 12/09  
100% complete |
| **2** | 04/10  
100% complete |
| **3** | 09/10  
10% complete |
Approach - Modify support via ion implantation

Optimize surface-catalyst interactions:
Ion implantation of HOPG with N, Ar, CF$_4$, I, S, B

Deposit PtRu catalyst:
sputtering, electrochemical deposition, microwave deposition

Catalyst characterization:
Microscopy (particle size, dispersion, composition), XPS (composition)
XRD (structure/phase, degree of alloying)

Measure methanol oxidation activity and durability:
High throughput electrochemical analysis

Optimize and down-select materials
composition, structure, phase, and particle size

Transfer process to high
surface area carbon

Scale up for DMFC MEA

DMFC Testing
Approach – First 7 months roadmap

Characterization:
Raman, XPS, TEM, SEM, XRD, XRF

Doped and Undoped HOPG

Metal Deposition

Electrodeposition

2:1 Pt:Ru atomic ratio

Metal particle coverage
Composition controlled

High metal loadings

Sputtering

Microwave deposition (MW)

1:1 Pt:Ru atomic ratio
Roughening of HOPG surface

High metal loadings

Optimization of interactions of Metal and support; role of defects, oxygen and nitrogen groups

MOR and durability
Technical Accomplishments – Understanding structural & chemical modification of N-HOPG via ion implantation

Ion implantation of N₂ longer than 45 seconds results in no additional structural disorder. Increase in the surface defects detected by Raman correlates with increase in both nitrogen and oxygen surface groups.

The relative amount of nitrogen (7%, via XPS) introduced into the carbon substrate also saturates after 45 seconds.

Optimum N-doping conditions are achieved at 45 sec.

Nitrogen is incorporated in the carbon network, resulting in formation of sp³-sp² bonding instead of sp²-sp² in graphitic structure and C-O, C=O and N-C=O.
Technical Accomplishments
High-throughput electrochemical screening

Designed and fabricated multi-electrode cell for electrochemical tests on an array of ion-implanted HOPG substrates;

Conducted tests on cartridge-style HOPG electrode holder

Custom-built multi-electrode half cell enables simultaneous electrochemical measurements on a multi-electrode array

Face Plate Made From PEEK

Cartridge-style electrode holder

Single electrode cartridge shown on a 5 cartridge-style electrode holder.

HOPG Array
Electrochemical data confirms 45 s N-HOPG is optimum for methanol oxidation activity.

Methanol oxidation current density at 0.65 V vs. NHE:
- 45 s N-HOPG: 7.9 uA/cm²
- 100 s N-HOPG: 0.8 uA/cm²

MOR Onset Potential vs. Implantation Time:
- Pt/Ru Black: 360 mV
- 45 s N-HOPG: 580 mV
- 100 s N-HOPG: 500 mV
- Undoped HOPG: 470 mV
- 1 s N-HOPG: 500 mV

20 potential pulses, applied at -0.3 V vs. RHE for 0.4 sec each on HOPG substrate [Pt(IV) and Ru(III) salts]
Technical Accomplishments – Effect of different dopants (electrodeposition of “low loading” PtRu on HOPG)

- The best dispersion of PtRu catalyst is obtained on N-doped sample.
- Ar-doping improved dispersion compared to undoped sample but resulted in a more pronounced agglomeration compared to N-doping.
- CF₄-doping possibly inhibits metal deposition
- Doping leads to expected decrease in the contact angle, N₂, Ar, CF₄<undoped
- Investigation of structure and composition of the doped HOPG samples is necessary to elucidate the differences in the metal deposition.

Potential pulses are applied at -0.3 V vs. RHE for 0.4 sec each
- 3-5 pulses for small particles
- 20-40 pulses for increased surface coverage
Technical Accomplishments and Progress
Electrodeposition of “high” loading PtRu on HOPG

N-doped: highest activity & best onset potential

PtRu/HOPG
PtRu/N-HOPG
PtRu/Ar-HOPG

Roughness Factor
i @ 650 mV

\[ \text{cm}^2_{\text{metal}} / \text{cm}^2_{\text{electrode}} \]
\[ \mu \text{A/cm}^2_{\text{metal}} \]

- PtRu/HOPG: 0.24, 1.5
- PtRu/N-HOPG: 1.47, 20.7
- PtRu/Ar-HOPG: 1.09, 5.4

\( \text{cm}^2_{\text{metal}} \) = area determined from CO stripping voltammetry
\( \text{cm}^2_{\text{electrode}} \) = geometric area
Technical Accomplishments and Progress
Microwave deposition of PtRu

N-doped, 40 pulses
Microwave-250 W - pulsed

E-chem PtRu N-HOPG
Microwave PtRu N-HOPG
JM HiSPEC 10000 PtRu/C

<table>
<thead>
<tr>
<th>Catalyst Type</th>
<th>Roughness Factor (cm²metal/cm²electrode)</th>
<th>Current Density i @ 650 mV (µA/cm²metal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-chem PtRu N-HOPG</td>
<td>1.5</td>
<td>20.7</td>
</tr>
<tr>
<td>Microwave PtRu N-HOPG</td>
<td>1.1</td>
<td>72.0</td>
</tr>
<tr>
<td>JM HiSPEC 10000 PtRu/C</td>
<td>22.5</td>
<td>58.0</td>
</tr>
</tbody>
</table>

Comparable performance to commercial catalyst (durability underway)
Technical Accomplishments and Progress
Sputtered Pt\textsubscript{1-x}Ru\textsubscript{x} Thin Films from single target

Pt composition after sputter from 50:50 Pt-Ru alloy target.

- The film/particle compositions can be effectively controlled with sputtering power
- Can deposit PtRu alloy or amorphous oxides, as thin films or particles
- Changing the chamber O\textsubscript{2} concentration impacts the Pt:Ru ratio of the films
- Experimentally can control composition, preferred orientation and phases
Technical Accomplishments and Progress
Synthesis capabilities for high surface area carbon

PtRu particle dispersion on Black Pearl carbon (1200 m²/g) via MW (70% Pt, 30% Ru by XRF)

MW Ruthenium particle deposition on chemical vapor deposition (CVD) synthesized B-doped carbon substrate (1100 m²/g)

Excellent dispersion of catalyst particles, similar to commercial grade.
(Electrochemistry characterization underway)
Technical Accomplishments and Progress
Powder ion implantation/Sputter chamber

Chamber is built for implanting ions and sputtering catalyst on high surface area carbon materials.
Technical Accomplishments and Progress

Focus: Enhance performance of methanol fuel cells with novel catalyst-substrate matrix.

1. Established an optimal N-implantation parameter set for HOPG
   - Demonstrated enhanced PtRu catalytic activity for methanol oxidation by achieving smaller particle size and higher dispersion of PtRu catalyst on N-doped carbon substrate.
   - Comparable performance to SOA catalyst (either electrochemical or microwave deposition).
   - Preliminary results suggest an apparent increase in durability of PtRu on N-doped HOPG as compared to undoped.

2. Sputter deposition of alloy with controlled composition from single alloy target.
   - Experimentally can control composition (%), preferred orientation (crystal face) and phases (hcp/fcc)

3. Established protocol for deposition of uniform PtRu catalysts particles on commercial and CVD synthesized B-doped and N-doped powders
   - Commercial grade dispersion on powders, evaluation underway.

4. Developed a process and built the chamber to implant ion and sputter PtRu onto carbon powders
Collaborations & Project Participants

- Develop novel catalyst-doped supports (NREL, CSM)
- Combinatorial electrode studies (JPL, NREL)
- Generate down-selected novel catalysts for DMFC membrane electrode assembly (MEA) (NREL, CSM, BASF*)
- MEA Evaluation (NREL, CSM, MTI#)

Accelerated built-up of team to accelerate progress:

**NREL:** Staff: Huyen Dinh, Thomas Gennett, David Ginley, Bryan Pivovar, Kevin O’Neill, Katherine Hurst, 
PostDocs: Arrelaine Dameron, Jennifer Leisch, Tim Olson, KC Neyerlin.

**CSM:** Prof. Ryan O’Hayre, Svitlana Pylypenko (postdoc) & graduate students

**JPL:** Staff: Charles Hays, Sri R. Narayanan

*Independent MEA performance evaluation
*Provide state of the art catalyst for benchmarking
Proposed Future Work

- Initiate implantation of other dopants into HOPG (B, S, I)
- Continue combinatorial electrochemical investigation of various implanted HOPG substrates (type and extent of dopant) (JPL)
- Investigate different methods to dope high surface area carbon (in situ and ex situ)
  - ion implantation, chemical vapor deposition, pyrolysis
- Investigate the effect of different high surface area carbon supports
- Characterize and measure methanol oxidation performance of PtRu/ doped high surface area carbon
- Select optimal materials, methods
- Construct MEAs from industrial standard PtRu catalyst and early generation tethered catalysts (PtRu/doped carbon)
- Measure DMFC performance and durability of tethered catalysts
Summary

**Relevance:** Focus on developing next generation DMFC anode catalyst materials that meet or exceed DOE’s 2010 performance, durability and cost targets for consumer electronics application to enable and accelerate the commercialization of DMFCs.

**Approach:** Modify HOPG surface with different dopants, via ion implantation, to better understand the effect of catalyst-support interaction on enhanced catalyst activity and stability of PtRu catalyst nanoparticles. Apply this dopant-engineering approach to develop advanced PtRu anode catalyst systems by doping high surface area carbon supports. This will improve catalyst utilization, activity, and durability at lower catalyst loading.

**Technical Accomplishments and Progress:** We have achieved significant progress to-date, including assembling the team and establishing capability quickly. We have met all project milestones (deadline extended for one FY’09 milestone). All subcontracts and funding are in place. We have established different PtRu deposition methods, optimized N-doping level (45 s) on HOPG via ion implantation, demonstrated that nitrogen implantation on HOPG enhanced the methanol oxidation activity and durability on PtRu catalyst, developed a processing system for ion implantation of high surface area carbon materials, and initiated study of high surface area carbon.

**Collaborations:** We have a diverse team of researchers with relevant expertise in materials synthesis and characterization and fuel cells, from several institutions including 2 national labs, a university, and 2 industry partners.

**Proposed Future Research:** We will study other dopants and transition from model HOPG substrate to real catalyst systems using high surface area carbon.
Supplemental Slides


PCA Analysis of Relationships

We use Principal Component Analysis (PCA) to elucidate the relationships between sputtering parameters, composition and structure, and electrochemical performance.

**PC1:**
- Higher pressure $\rightarrow$ increase in [200] phase $=$ largest effect on MOR Peak Current
- Higher %Pt $\rightarrow$ higher Currents

**PC2:**
- Higher DC Power and Total Power $\rightarrow$ higher %Pt $\rightarrow$ more positive onset potential
- Lower DC Power and Total power $\rightarrow$ higher %Ru and higher ratio of [200]/[111] $\rightarrow$ more negative Onset Potential and higher Currents

**PC3:**
- Lower RF Power and lower Total Power, as well as lower Pressure result in more FCC structure and more positive MOR peak potential
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**PC3:**
- Lower RF Power and lower Total Power, as well as lower Pressure result in more FCC structure and more positive MOR peak potential
Preliminary durability of microwave deposited PtRu catalysts on N-doped HOPG

PtRu nanoparticles deposited on N-doped HOPG, via a microwave, are highly dispersed compared to PtRu catalysts deposited on undoped HOPG. PtRu nanoparticles on the N-doped HOPGs are stable after 10,000 cycles between 0 and 1.2 V vs. Ag/AgCl.
Technical Accomplishments - Durability of MW deposited PtRu catalysts on N-doped HOPG

PtRu nanoparticles on the N-doped HOPGs are stable after 10,000 cycles (Low mass Loading)

10,000 cycles between 0 and 1.2 V vs. Ag/Ag/Cl.
CO stripping

<table>
<thead>
<tr>
<th>Material</th>
<th>CO stripping</th>
<th>RF</th>
<th>i @ 650 mV</th>
</tr>
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<tbody>
<tr>
<td>Pt Poly</td>
<td>2.2</td>
<td>1.3</td>
<td>3.9</td>
</tr>
<tr>
<td>Ru Black</td>
<td>22.9</td>
<td>13.9</td>
<td>11.9</td>
</tr>
<tr>
<td>PtRu Black</td>
<td>23.0</td>
<td>14.0</td>
<td>83.3</td>
</tr>
<tr>
<td>Pt20Ru10 CB</td>
<td>16.0</td>
<td>9.7</td>
<td>34.5</td>
</tr>
<tr>
<td>Pt40Ru20 CB</td>
<td>37.0</td>
<td>22.5</td>
<td>58.0</td>
</tr>
<tr>
<td>Pt40Ru20 CCB</td>
<td>33.0</td>
<td>20.0</td>
<td>45.7</td>
</tr>
</tbody>
</table>
XPS: Structural & chemical modification of HOPG

**N 1s**
- **45 sec**
  - Pyrrolic
  - Pyridinic
  - Graphytic
  - N-oxides
  - Imine

**C 1s**
- **45 sec**
  - HOPG defects
  - Various C-N and C-O bonds

**Partial conversion to pyridinic-N**
- Representative of 15-100 sec

**N 1s**
- **1 sec**
  - Pyrrolic-N is dominant
- **5 sec**
  - Graphitic
- **45 sec**

**C 1s**
- **45 sec**
- **5 sec**
- **1 sec**
  - HOPG defects
  - Various C-N and C-O bonds are formed