Argonne NATIONAL LABORATORY

*... for a brighter future*

U.S. Department of Energy

UChicago Argonne LLC

Office of Science U.S. DEPARTMENT OF ENERGY

A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

## 2014 DOE Hydrogen and Fuel Cells Program Review

# Nanosegregated Cathode Catalysts with Ultra-Low Platinum Loading

**Announcement No:** DE-PS36-08GO98010

**Topic:** 1A


**PIs:** Vojislav R. Stamenkovic
Nenad M. Markovic

**Materials Science Division**

**Argonne National Laboratory**


Project ID# FC008

# Overview

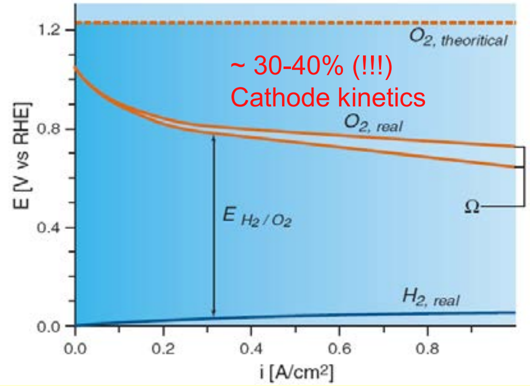
## Timeline

- Project start: 9/2009
- Project end:  9/2014

## Budget

- Total Project funding  $ 5.1M
  - DOE share: 80 %
  - Contractor share: 20%
- Funding for FY13:  $ 1.2M
- Planned FY14 DOE Funding: $763,856

## Barriers




1) Durability of fuel cell stack

2) Cost (catalyst, membrane, gdl)

3) Performance   (losses and activity)

## Partners:

- **Oak Ridge National Laboratory** – Karren More
- **Jet Propulsion Laboratory** – C. Hays (FY10-12)
- **Brown University** – Shouheng Sun
- **University of Pittsburgh** – Goufeng Wang
- **3M Company** – Radoslav Atanasoski

## Project Lead:

- **Argonne National Laboratory**

# Relevance

***Objectives*** **The main focus of ongoing DOE Hydrogen & Fuel Cell Program is development of highly-efficient and durable multimetallic PtMN (M, N = Co, Ni, Fe, V, T)** ***nanosegregated catalysts*** **for the oxygen reduction reaction** ***with ultra low-Pt content***

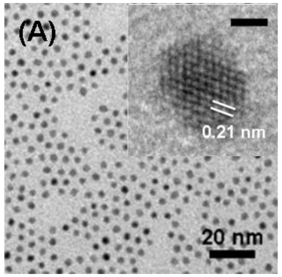
## DOE Technical Targets

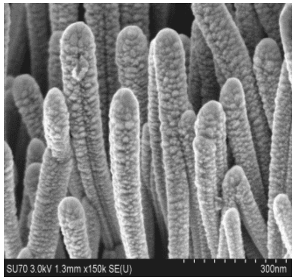
- Specific activity @0.9$V_{iR\text{-}free}$: 720 $\mu A/cm^2$
- Mass activity @0.9V: 0.44 $A/mg_{Pt}$
- Electrochemical area loss: < 40%
- Catalyst support loss: < 30%
- PGM Total content: 0.2 g/kW
- PGM Total loading: 0.2 $mg/cm^2_{electrode}$
- Cost*: $ 30/$kW_e$
- Durability w/cycling (80$^o$C): 5000 hrs

*based on Pt cost of $450/troy ounce

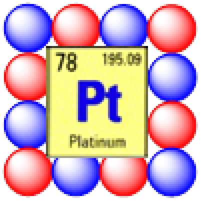
## ANL Technical Targets

- Specific activity @ 0.9$V_{iR\text{-}free}$
  2015 DOE target x 3
- Mass activity @ 0.9$V_{iR\text{-}free}$
  2015 DOE target x 3
- Electrochemical area loss
  2015 DOE target
- PGM Total content
  < 0.1g/kW

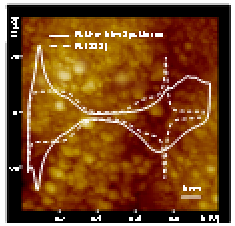


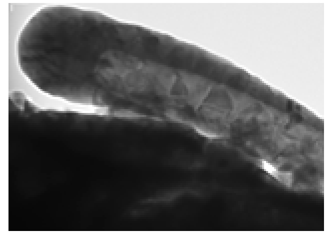



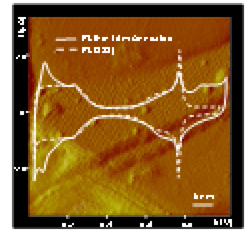
# Approach



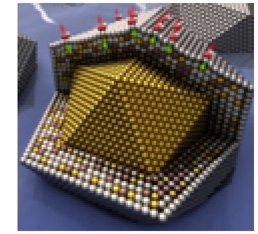

EXTENDED Multi-M SURFACES







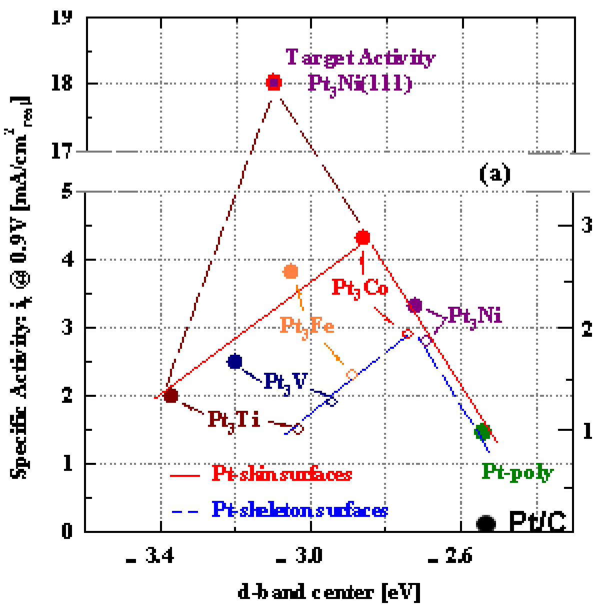
THIN METAL FILMS / MODEL NANOPARTICLES



NANOPARTICLES

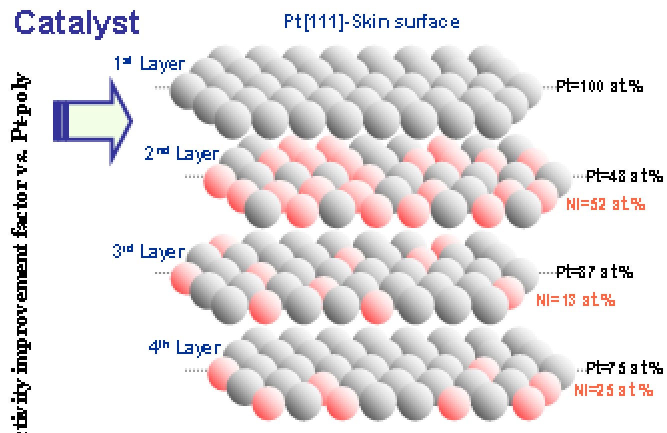
Materials-by-design approach - by ANL to design, characterize, understand, synthesize/fabricate, test and develope advanced nanosegregated multi-metallic nanoparticles and nanostructured thin metal films

## Well-Defined Systems



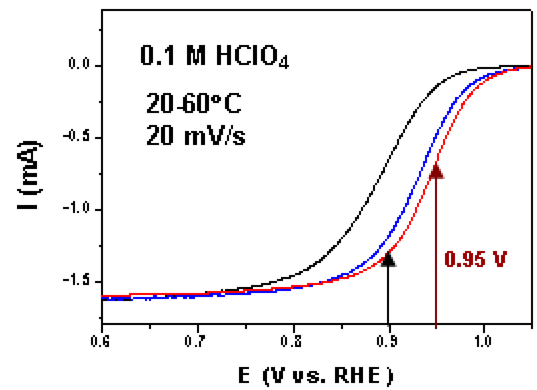

Advanced Nanoscale Catalyst

## Nanosegregated Profile




$Pt_3Ni(111)$-Skin ~100 times more active than the state-of-the-art Pt/C catalysts

## Intrinsic Activity




RDE:
- ORR activity measured at 0.95V
- iR corrected currents
- Measurements without ionomer

- Rational synthesis based on well-defined systems
- Addition of the elements that hinder Pt dissolution
- Activity boost by lower surface coverage of spectators
- Prevent loss of TM atoms without activity decrease

# Approach / Milestone

(Go-No Go Decision Met)

**Milestone 1.** Fundamental understanding (FY09-13) (Accomplished)

1.1 Resolved electronic/atomic structure and segregation profile (100%)

1.2 Confirmed reaction mechanism of the ORR (100%)

1.3 Improved specific and mass activity (95%)

**Milestone 2.** Synthesis and characterization (FY10-14)

2.1 Physical methods: TM films (5-10 layers), nanoparticles (5-300 nm) (95%)

2.2 Established chemical methods: colloidal and impregnation synthesis (95%)

2.3 Characterization: Ex-situ (UHV, TEM) and in-situ (EXAFS, EC) (100%)

2.4 Theoretical modeling (DFT, MC) methods (95%)

**Milestone 3.** Fabrication and testing (FY11-14)

3.1 New $PtM_1M_2$ catalysts with higher activity and improved durability (95%)

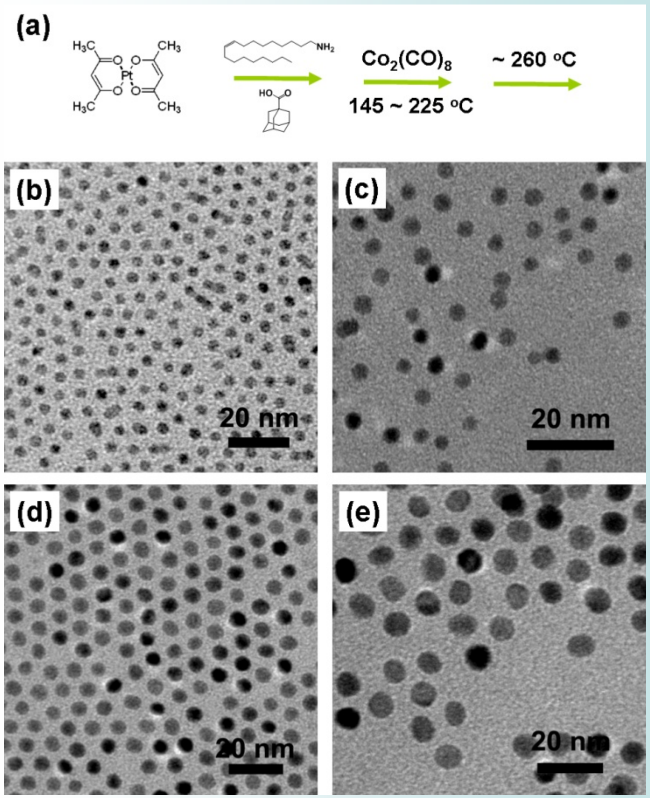
3.2 Carbon support vs. nanostructured thin film catalysts (95%)

3.3 MEA testing (50 $cm^2$) of the optimized catalysts (55%)

3.4 Scale up of the catalyst fabrication in lab environment (70%)

# Technical Accomplishments FY09 -13: *Pt-alloy Nanocatalysts*

**Colloidal solvo - thermal approach** has been developed for monodispersed PtMN NPs with **controlled size and composition**




**Efficient surfactant removal** method does not change the catalyst properties

## 1° Particle size effect applies to Pt-bimetallic NPs

**Specific Activity** increases with particle size: 3 < 4.5 < 6 < 9nm

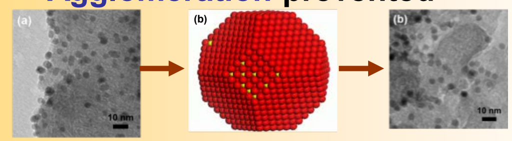
**Mass Activity** decreases with particle size

**Optimal size particle size** ~5nm

*J. Phys. Chem. C.*, 113 (2009) 19365

## 2° Temperature induced segregation in Pt-bimetallic NPs

**Agglomeration** prevented

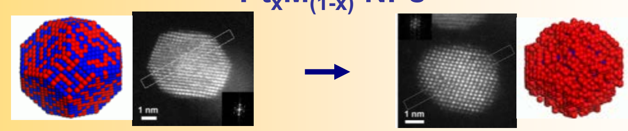


**Optimized annealing** temperature 400-500°C

*Phys.Chem.Chem.Phys.*, 12 (2010) 6933

## 3° Surface chemistry of homogeneous Pt-bimetallic NPs

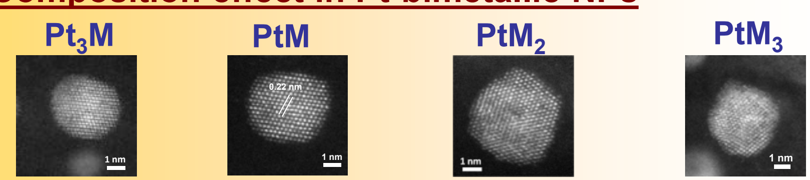
$Pt_xM_{(1-x)}$ NPs



**Dissolution** of non Pt surface atoms leads to **Pt-skeleton** formation

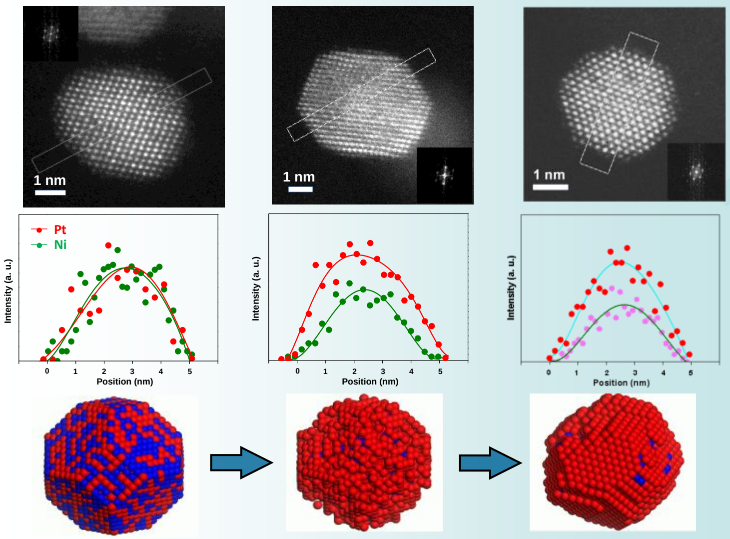
*Adv. Funct. Mat.*, 21 (2011) 147

## 4° Composition effect in Pt-bimetallic NPs




**Optimal** composition of Pt-bimetallic NPs is PtM

# Technical Accomplishments FY09-13: *Pt-alloy Nanocatalysts*

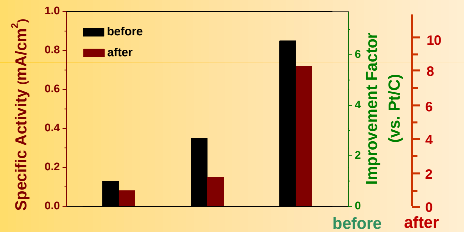


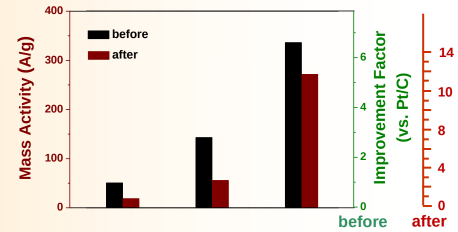

## 5º Pt-bimetallic catalysts with mutilayered Pt-skin surfaces

Synthesized PtNi NPs have homogeneous distribution of Pt, Ni

3-4ML of Pt-skeleton surfaces for PtNi acid leached NPs

Multilayered Pt-skin surfaces confirmed for PtNi annealed NPs

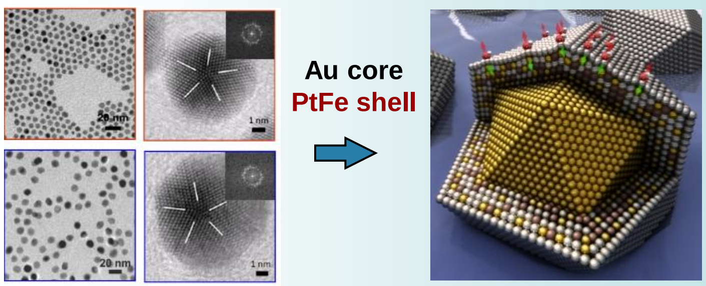


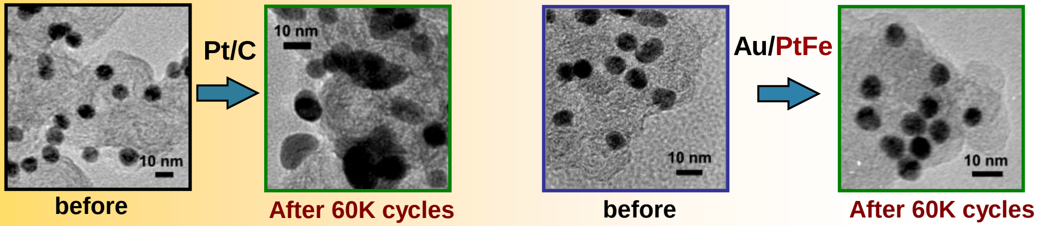

**RDE after 4K cycles @60ºC (0.6-1.05V vs. RHE):**

**8-fold specific and 10-fold mass activity improvements over Pt/C**

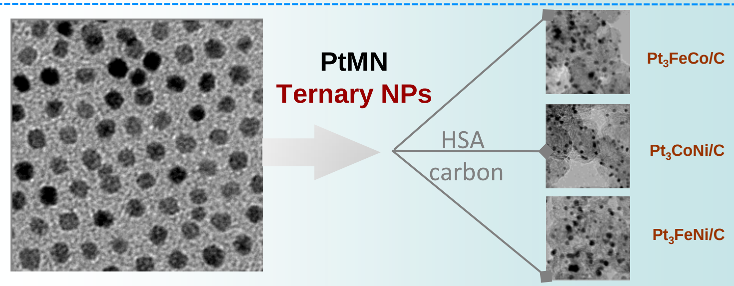
*JACS*, 133 (2011) 14396



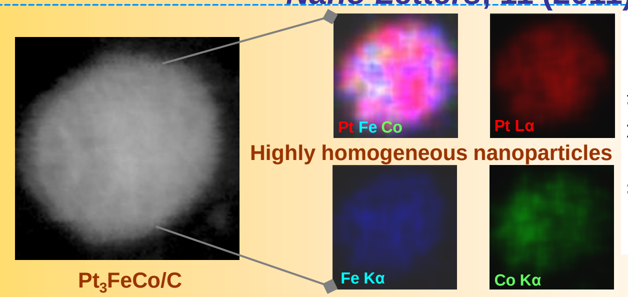

## 6º Multimetallic NPs can further improve activity and durability

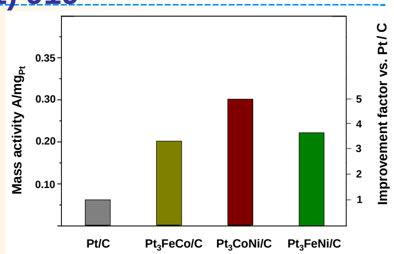



*Nano Letters*, 11 (2011) 919



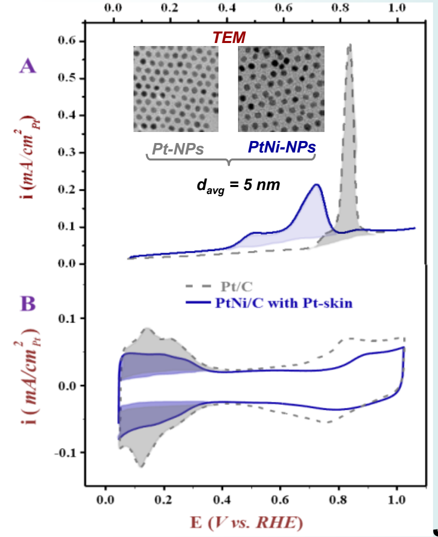

*J. Phys. Chem. Letters*, 3 (2012) 1668

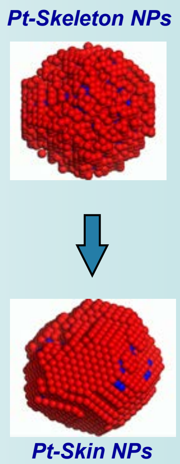



Additional gain in mass and specific activities vs. Pt and $Pt_3M$ alloys

# Technical Accomplishments FY09-13: *Pt-alloy Nanocatalysts*




*JACS* 133 (2011) 14396

## 7° Electrochemically active surface area of Pt-Skin catalysts

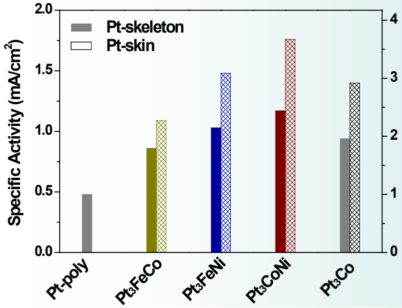
Catalysts with multilayered Pt-skin surfaces exhibit substantially lower coverage by $H_{upd}$ vs. Pt/C
(up to 40% lower $H_{upd}$ region is obtained on Pt-Skin catalyst)

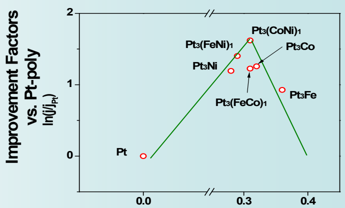
Surface coverage of adsorbed CO is not affected on Pt-skin surfaces

Ratio between $Q_{CO}/Q_{Hupd}$>1 is indication of Pt-skin formation

Electrochemical oxidation of adsorbed CO should be used for estimation of EAS of Pt-skin catalysts

Benefits: to avoid overestimation of specific activity



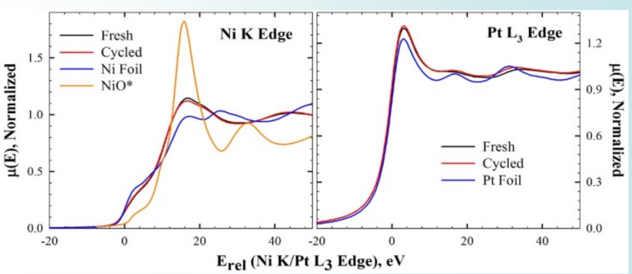




## 8° Multimetallic $Pt_3NM$ alloys can further improve activity

Similarly to $Pt_3M$ alloys, ternary alloys form Pt-skeleton and Pt-skin surfaces depending on the surface treatment

The most active alloy is $Pt_3NiCo$, with 4-fold improvement factor in specific activity compared to Pt-poly

*J. Phys. Chem. Letters*, 3 (2012) 1668



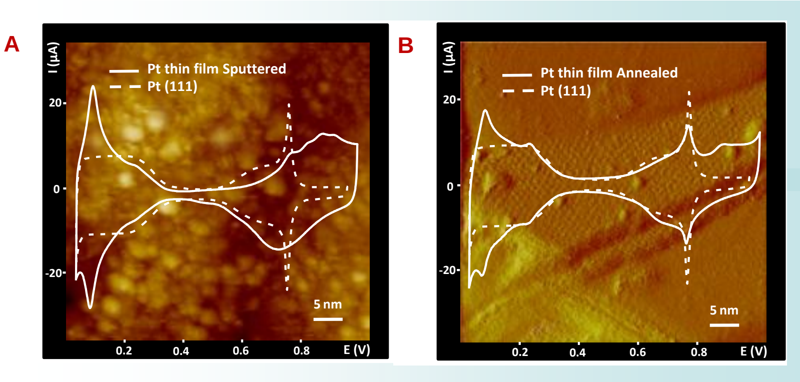

## 9° MEA: PtNi-MLSkin/NPs 20,000 potential cycles, 0.6 – 0.95 V

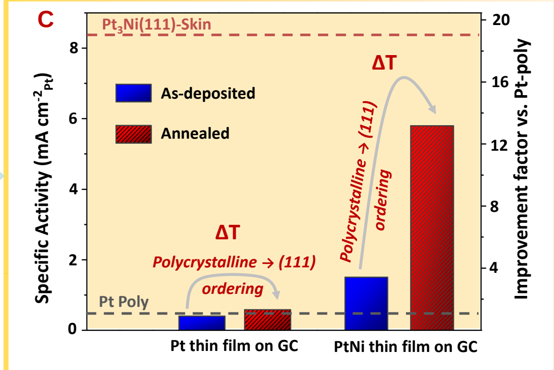
No change in Ni and Pt edges after 20K cycles confirms high stability pf multilayered Pt-Skin under operating conditions

Specific surface area loss was only 12%, while Pt/C catalysts suffer loss of 20-50%

***Unpublished***

# Technical Accomplishments FY09-13: *Pt-alloy Nanocatalysts*



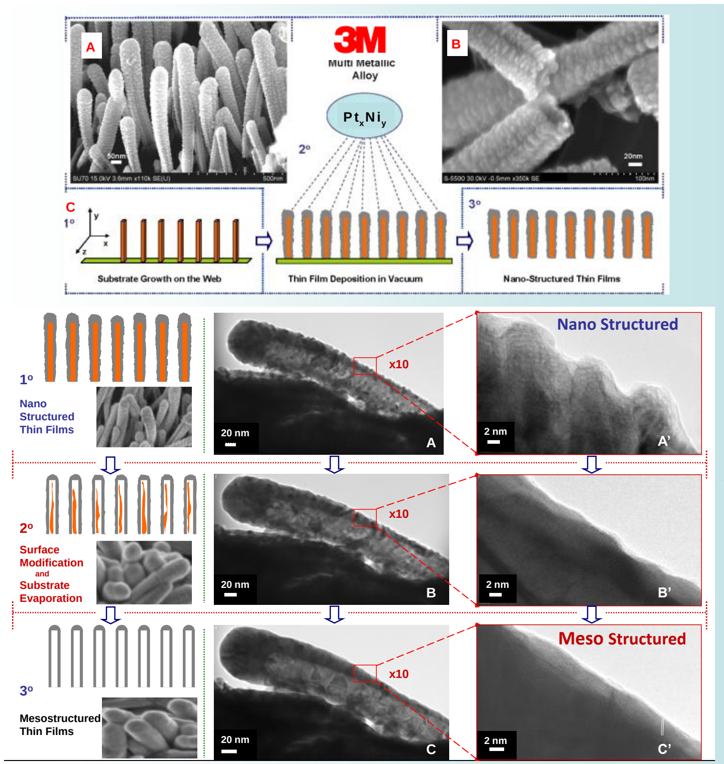




## Scientific Achievement

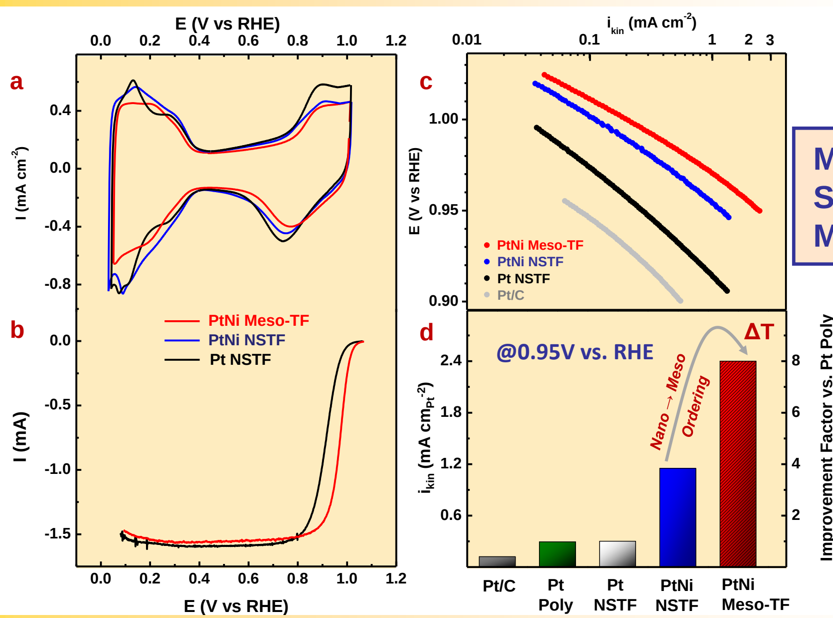
Control of surface structure and morphology of multimetallic thin films without use of templates for epitaxial growth

## Significance and Impact

Enables electrocatalytic properties of Pt-alloy single crystals in thin film materials



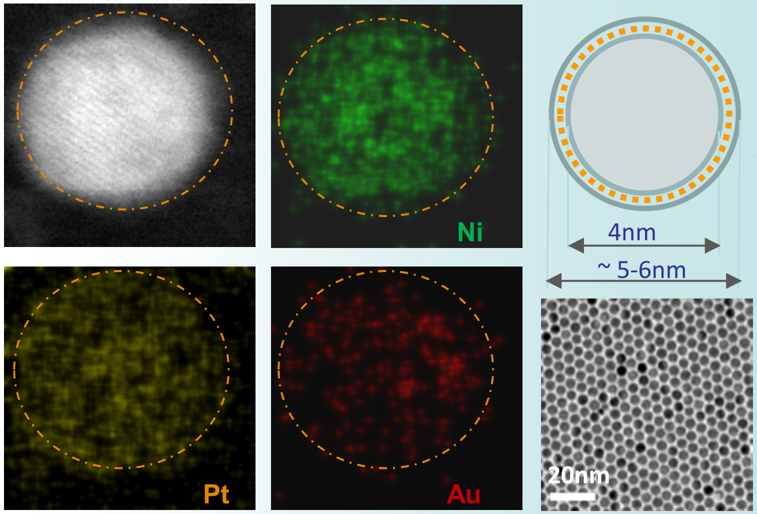

## 10º Mesostructured Thin Films with Tunable Morphology



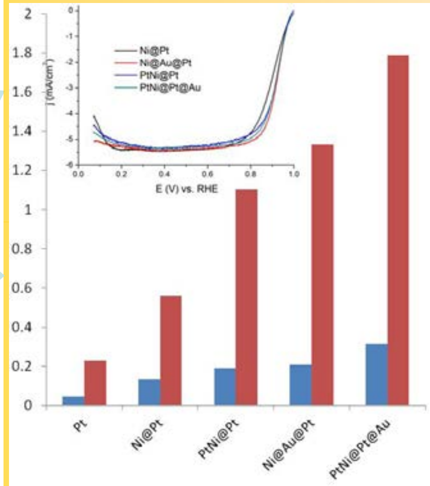

**MSTF vs. Pt/C:**
**SA 20-fold**
**MA 6-fold**

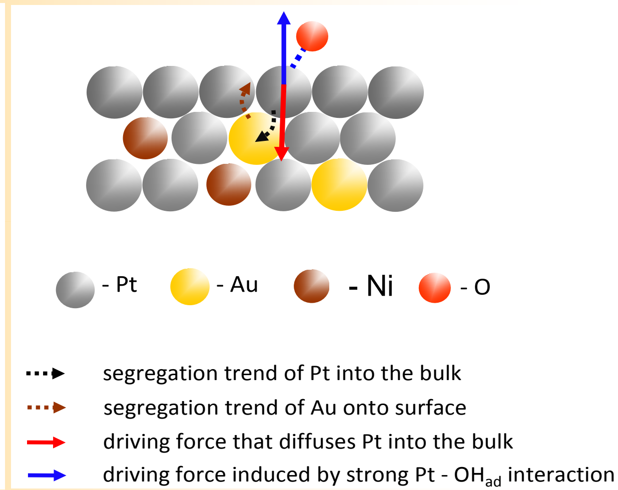
*Nature Materials*, 11 (2012) 1051

# Technical Accomplishments FY09-13: *Pt-alloy Nanocatalysts*

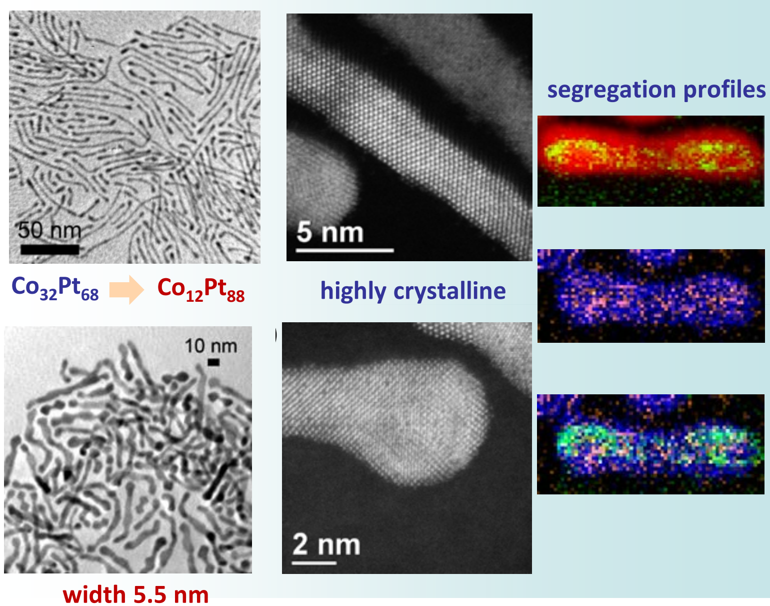



## 11° Core-Shell particles with Au interlayer

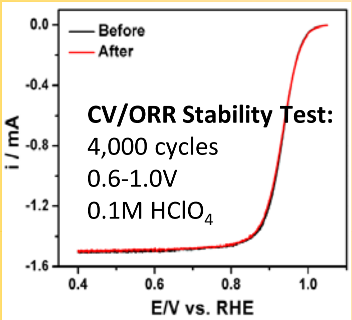


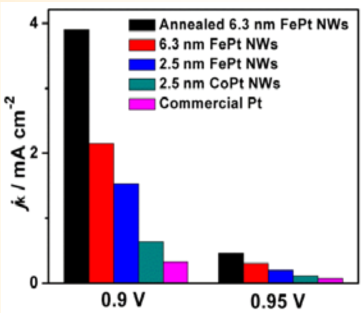




***Unpublished***




## 12° Highly active and durable multimetallic NWs



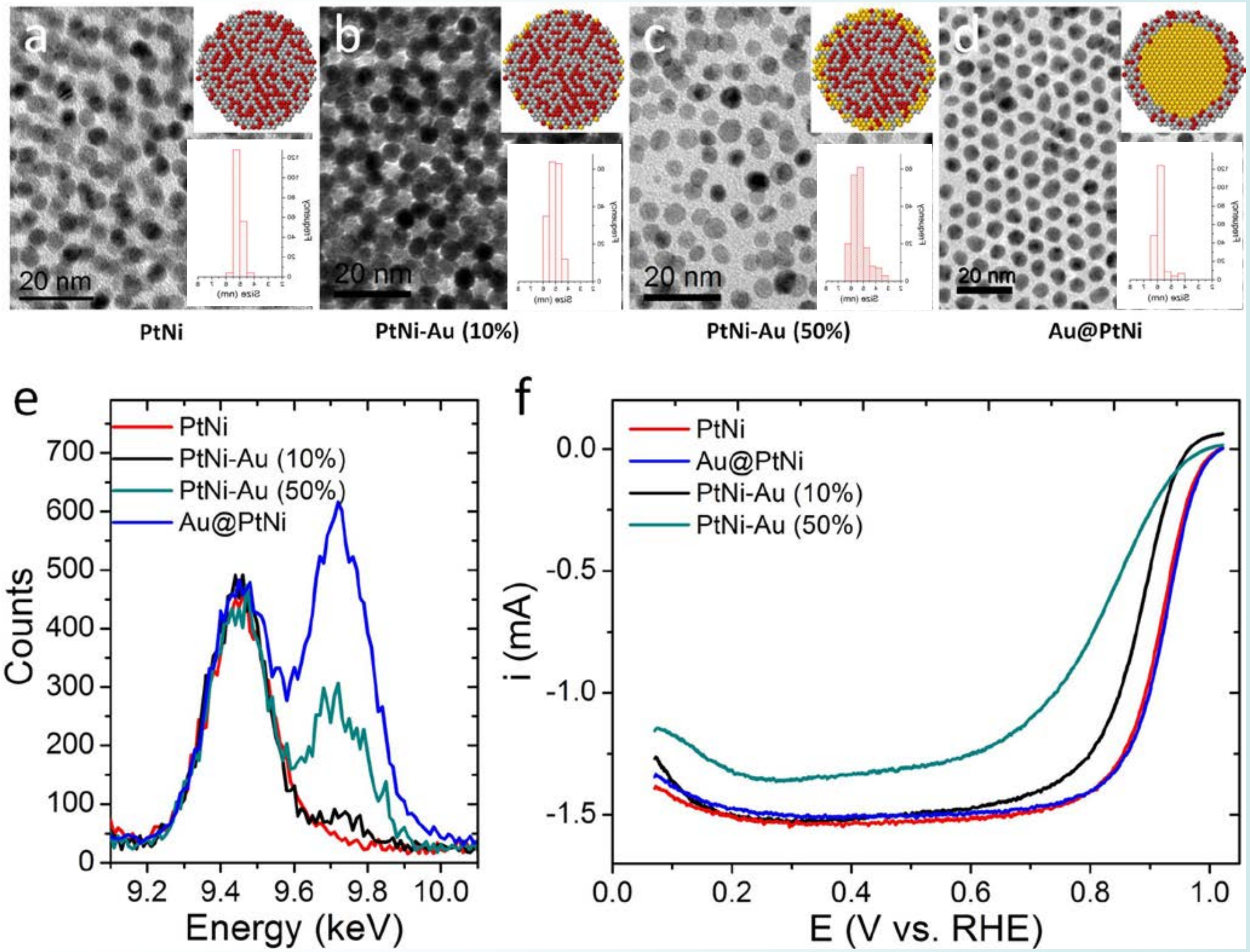

Pt Alloy NWs are active and durable catalyst with no change in activity after 4,000 cycles
Specific activity depends on the composition and width of NWs
Annealing of NWs induces formation of nanosegregated profile with Pt-Skin type of surface
Pt-Skin confirmed by suppressed $H_{upd}$, Pt-OH shift, $CO_{ad}$/Hupd ratio, and high ORR activity

***Angew. Chem. Int.Ed.*, 52 (2013) 3465**

# Accomplishments and Progress: *Core/Shell NPs with Au interlayer*

## *Synthesis, Structural and Electrochemical evaluation of core shell NPs*

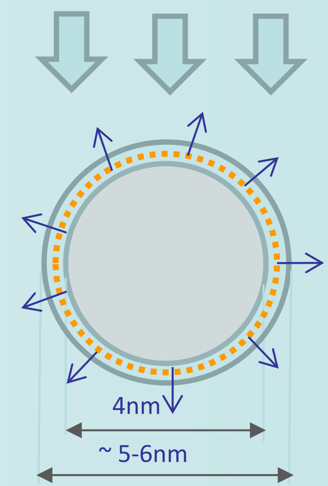
### Influence of surface Au on the ORR catalytic performance




Surface Au decreases total number Pt active sites for adsorption of $O_2$

Au core / PtNi shell NPs have the same catalytic activity as PtNi NPs

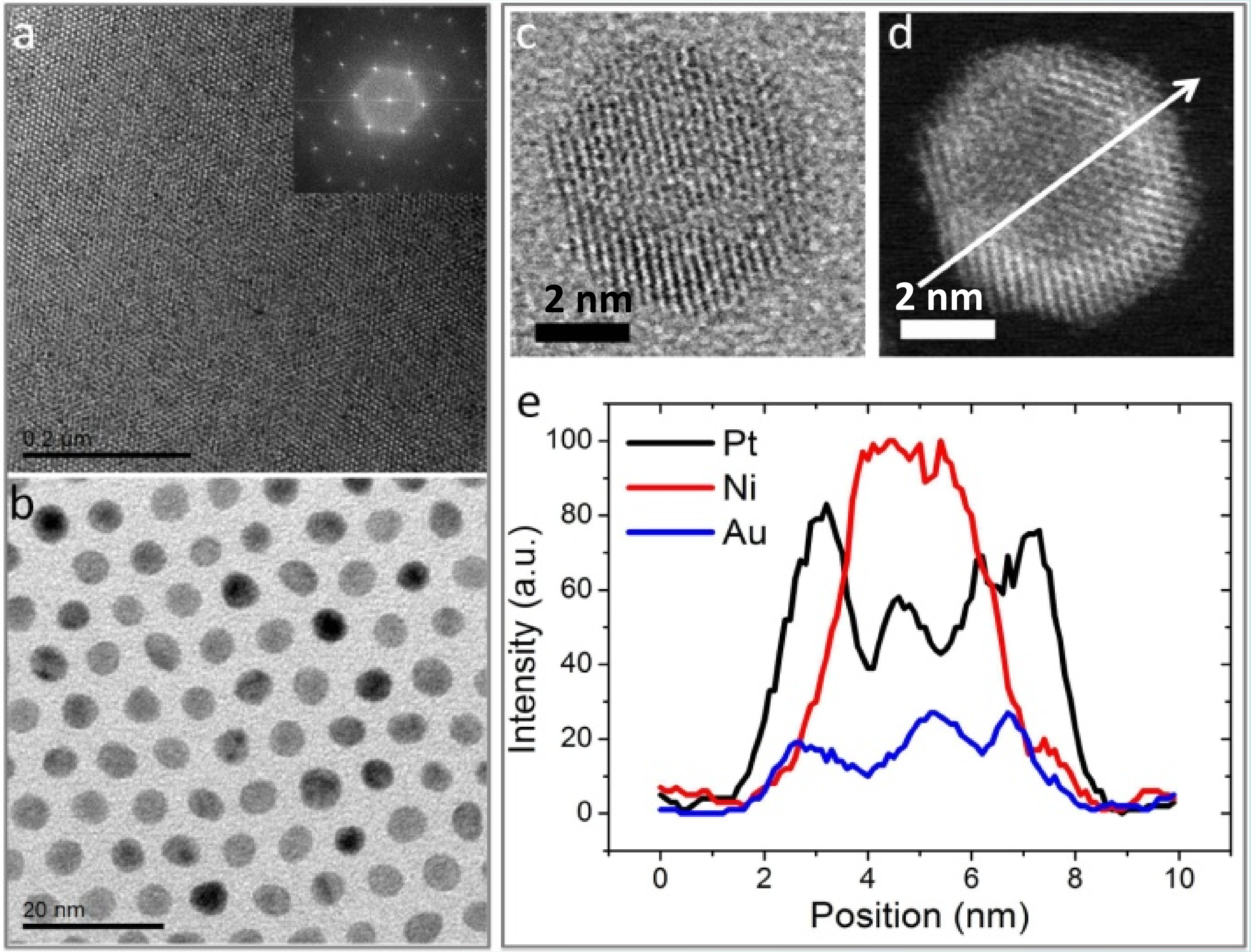
Subsurface Au does not alter catalytic properties of NPs

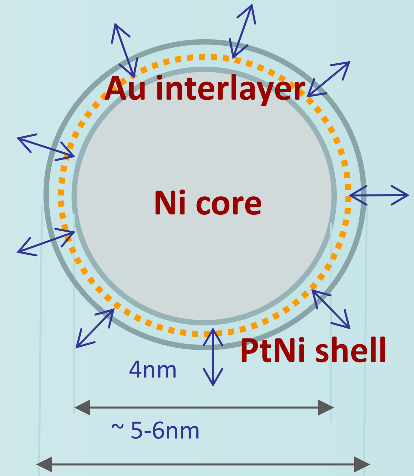


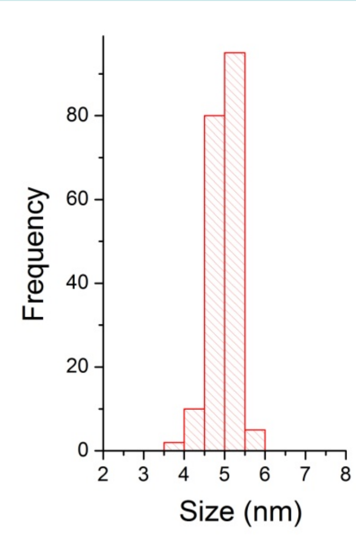

**Ni core / Au interlayer / PtNi shell**

# Accomplishments and Progress: *Core/Shell NPs with Au interlayer*

## *Synthesis, Structural and Electrochemical evaluation of core shell NPs*



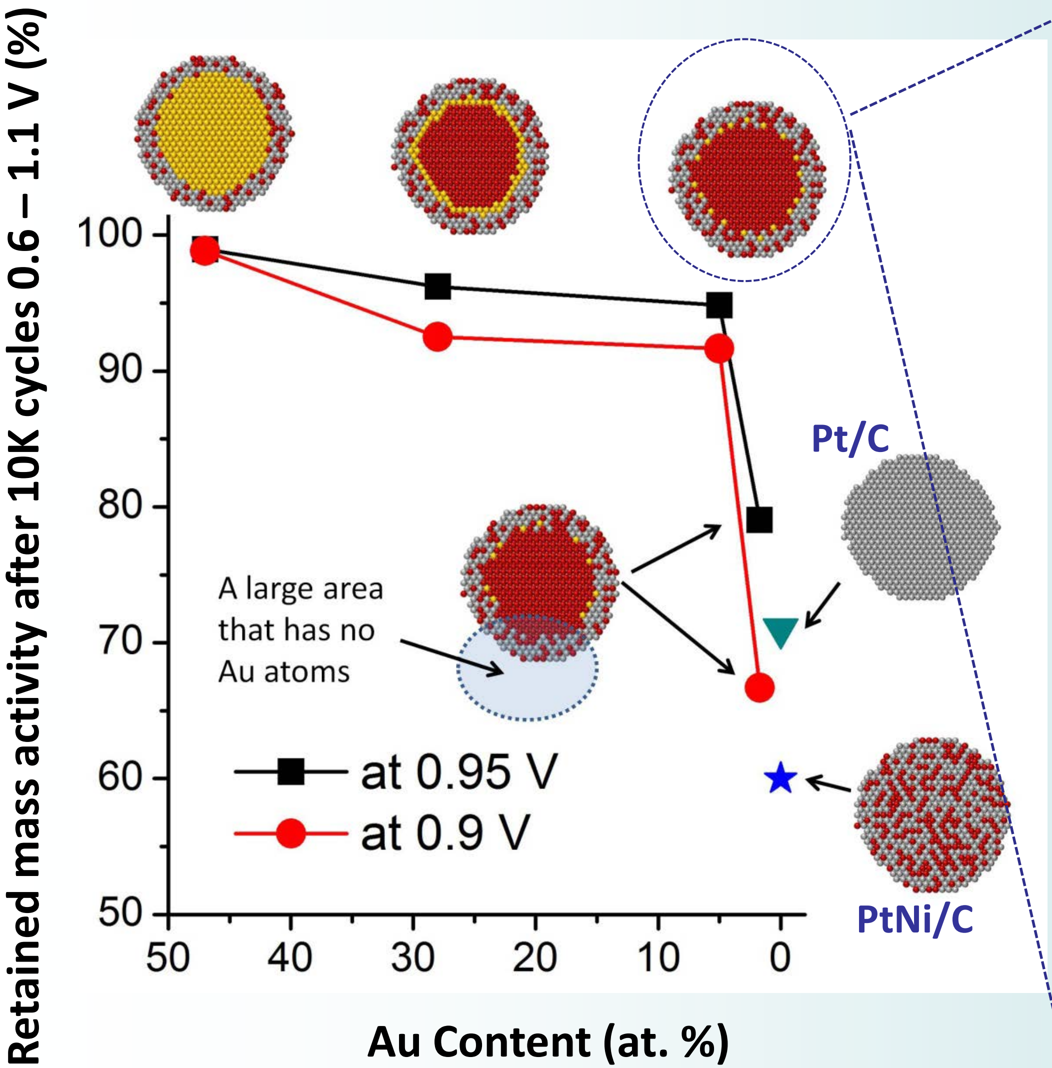



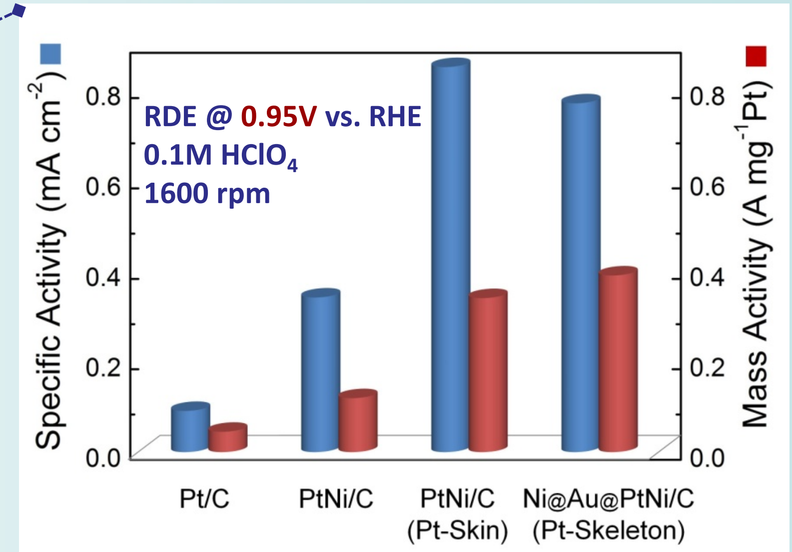



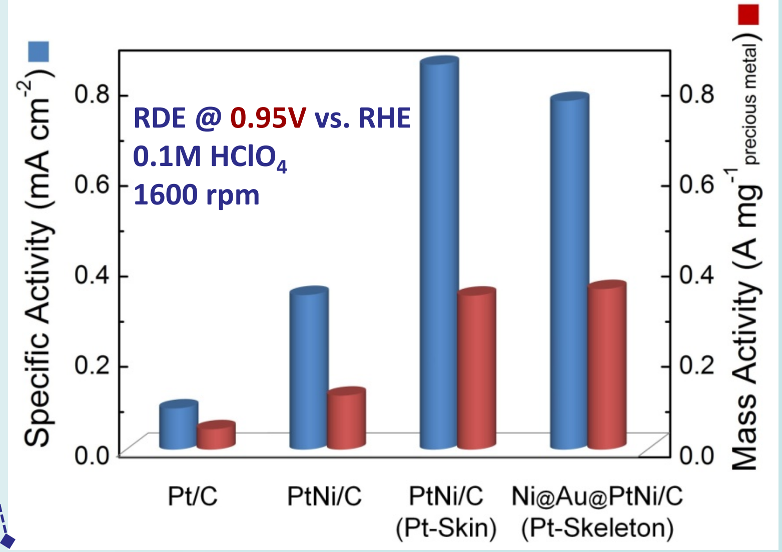

**Monodisperse , Core/Interlayer/Shell NPs: Ni core / Au interlayer / PtNi shell**

# Accomplishments and Progress: *Core/Shell NPs with Au interlayer*

## *Synthesis, Structural and Electrochemical evaluation of core shell NPs*

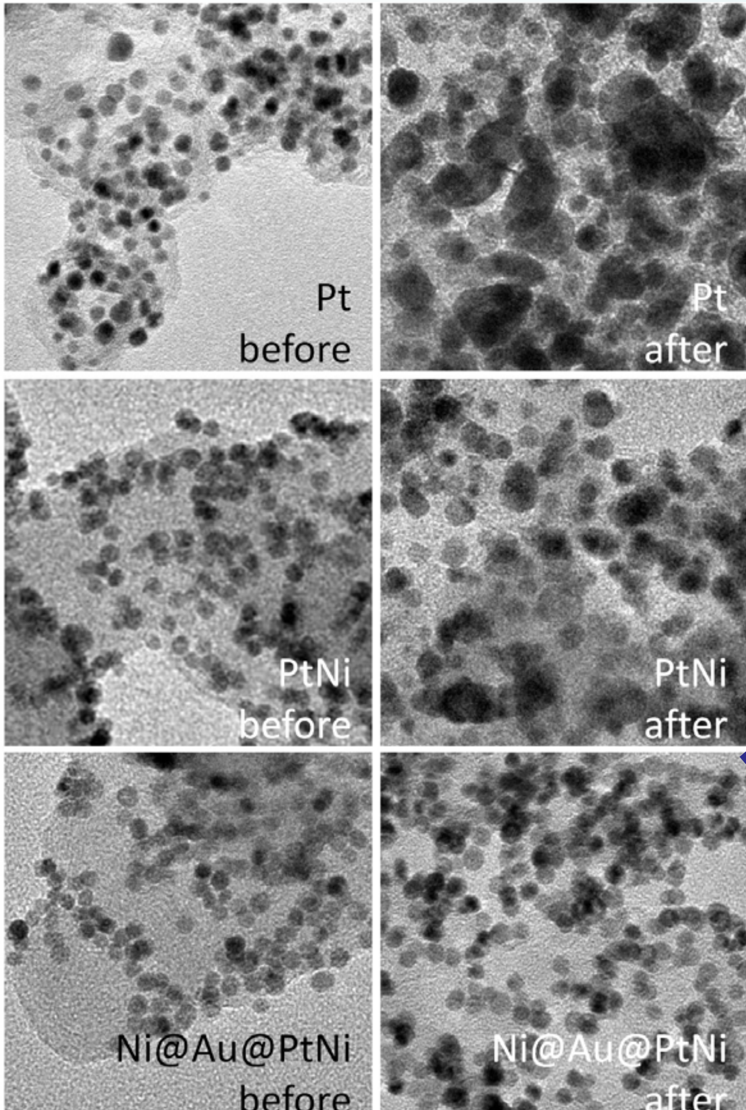


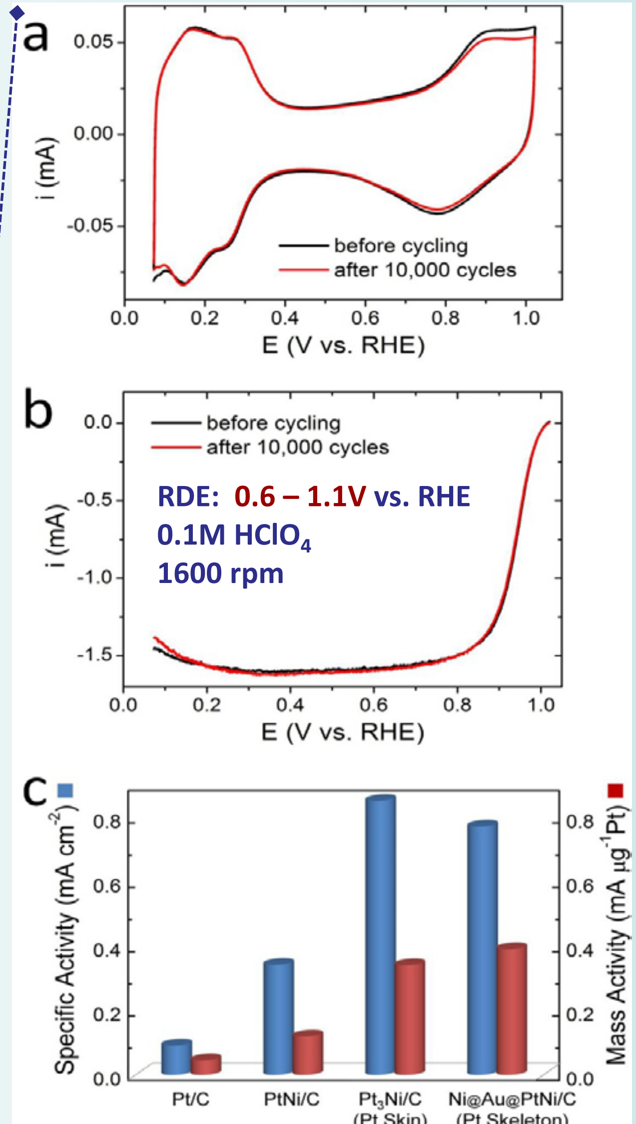



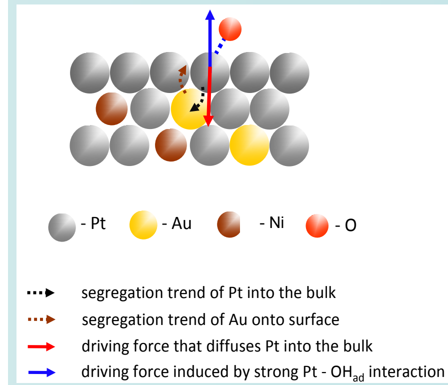
# Accomplishments and Progress: *Core/Shell NPs with Au interlayer*

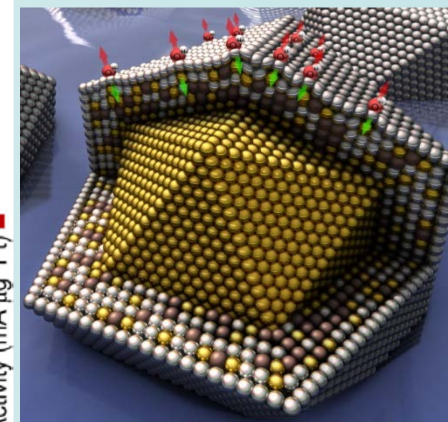
## *Synthesis, Structural and Electrochemical evaluation of core shell NPs*



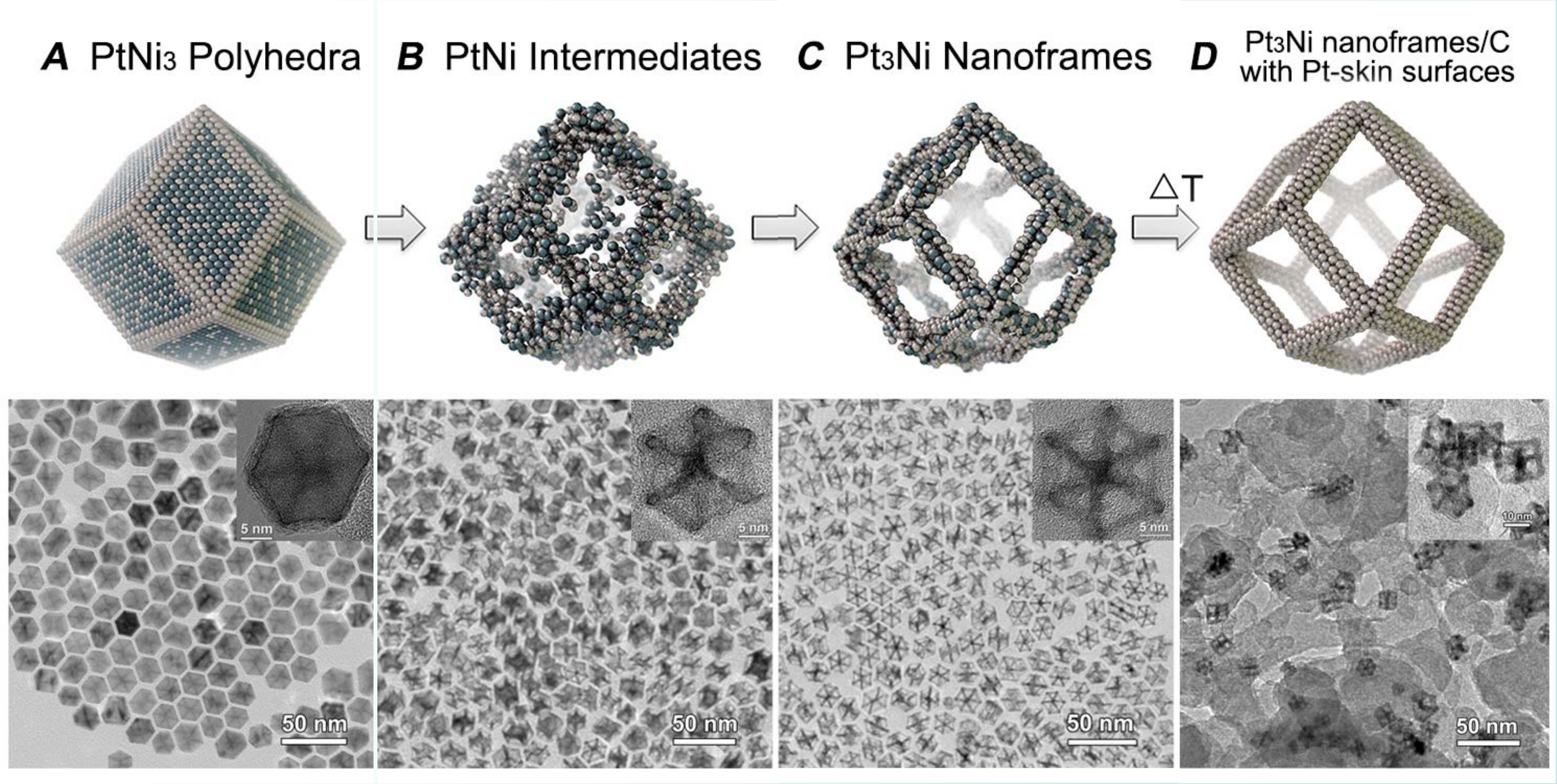

### Stabilization mechanism



# Accomplishments and Progress: *PtNi Nanoframes*

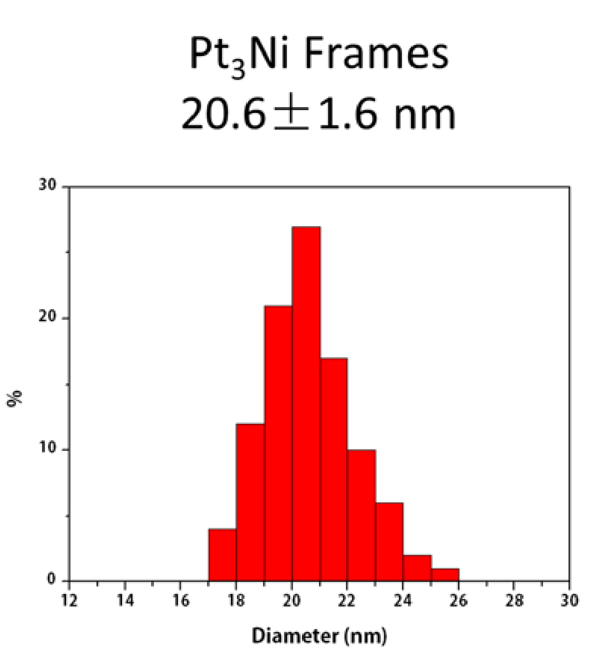
## *Synthesis, Structural and Electrochemical evaluation of Nanoframes*

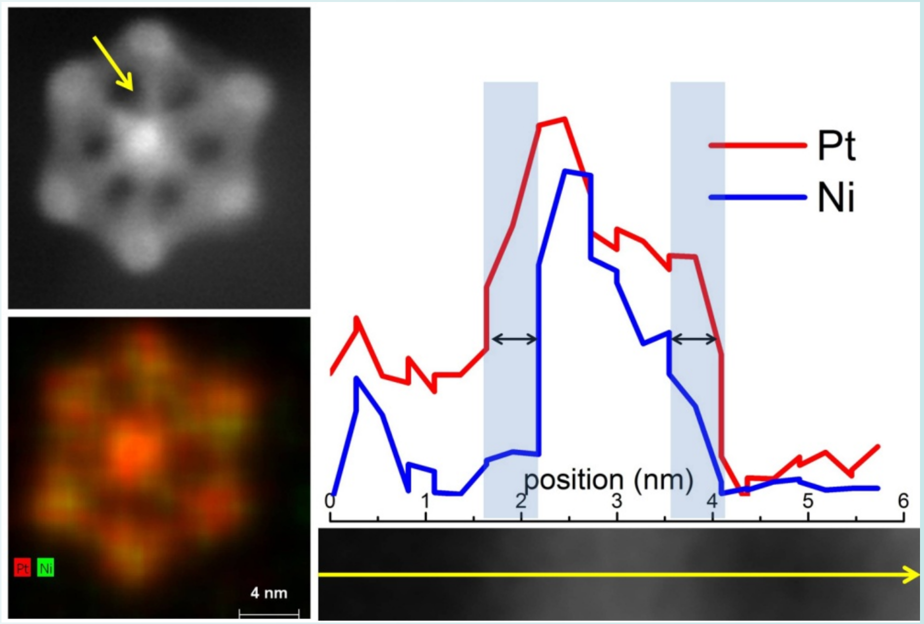



- **$H_2PtCl_6$ and $Ni(NO_3)_2$ react in oleylamine at 270°C for 3 min forming solid $PtNi_3$ polyhedral NPs**
- **Reacting solution is exposed to $O_2$ that induces spontaneous corrosion of Ni**
- **Ni rich NPs are converted into $Pt_3Ni$ nanoframes with Pt-skeleton type of surfaces**
- **Controlled annealing induces Pt-Skin formation on nanoframe surfaces**

# Accomplishments and Progress: *PtNi Nanoframes*

## *Synthesis, Structural and Electrochemical evaluation of Nanoframes*

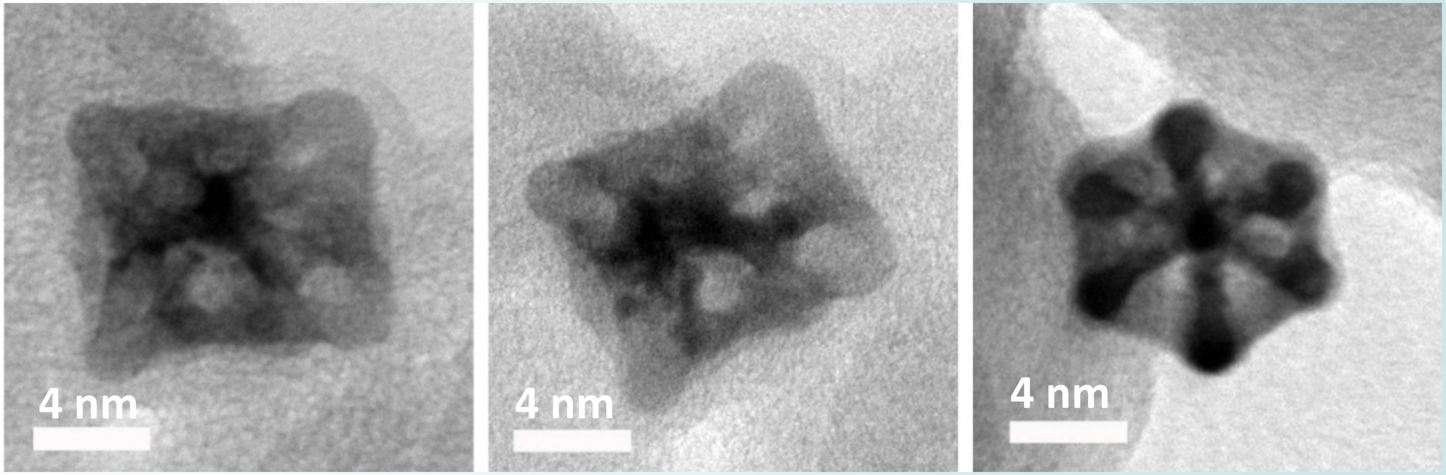


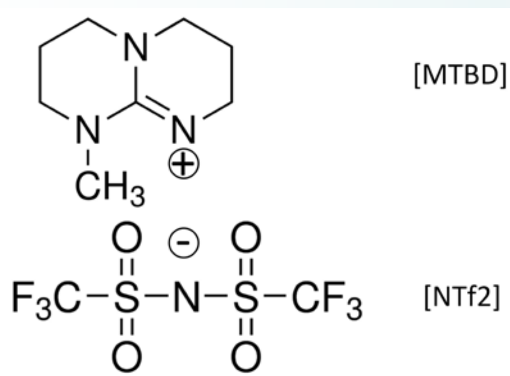




- Narrow particle size distribution
- Hollow interior
- Formation of Pt-skin with the thickness of 2ML
- Surfaces with 3D accessibility for reactants
- Segregated compositional profile with overall $Pt_3Ni$ composition

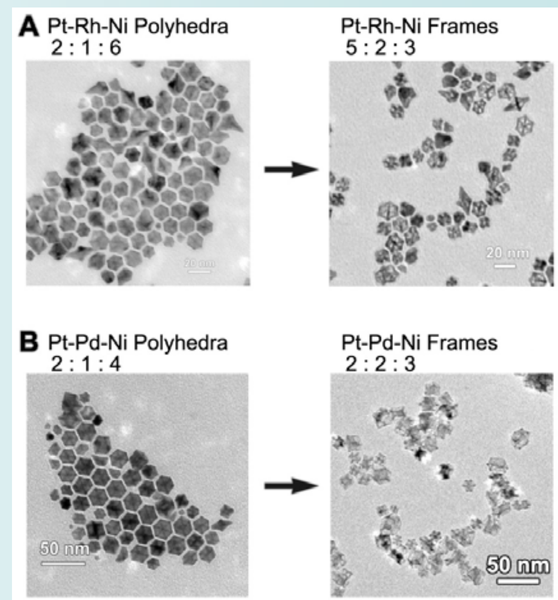
# Accomplishments and Progress: *PtNi Nanoframes*

## *Incorporation of Ionic Liquid Into the Nanoframes*



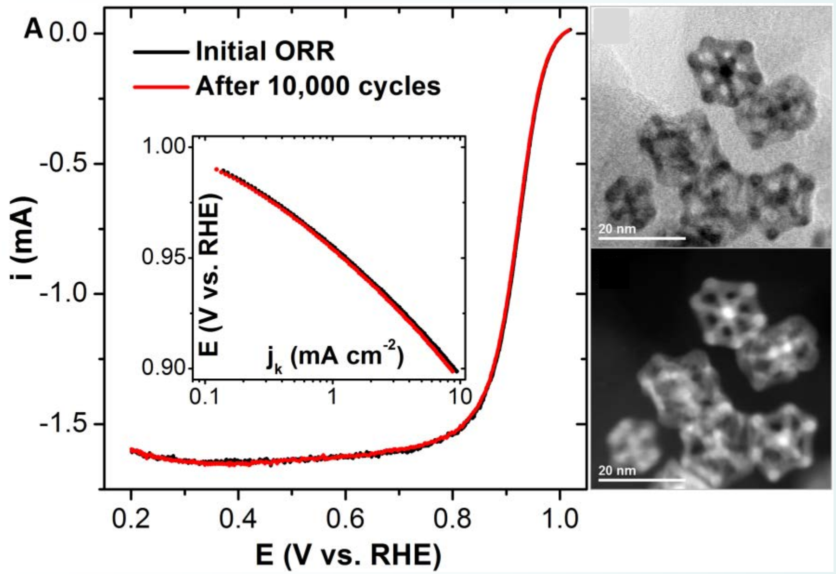



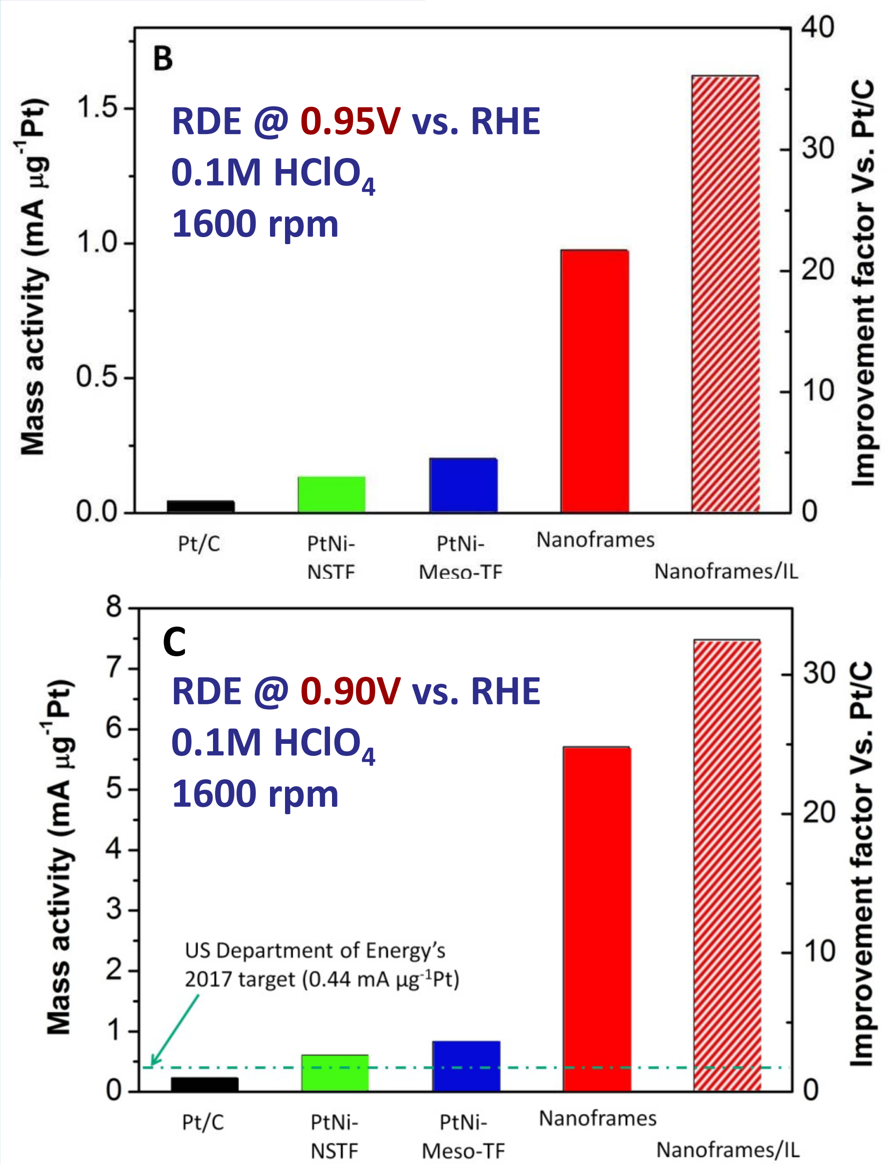

7-methyl-1,5,7-triazabicyclo[4.4.0]dec-5-ene [MTBD]



# Accomplishments and Progress: *PtNi Nanoframes*

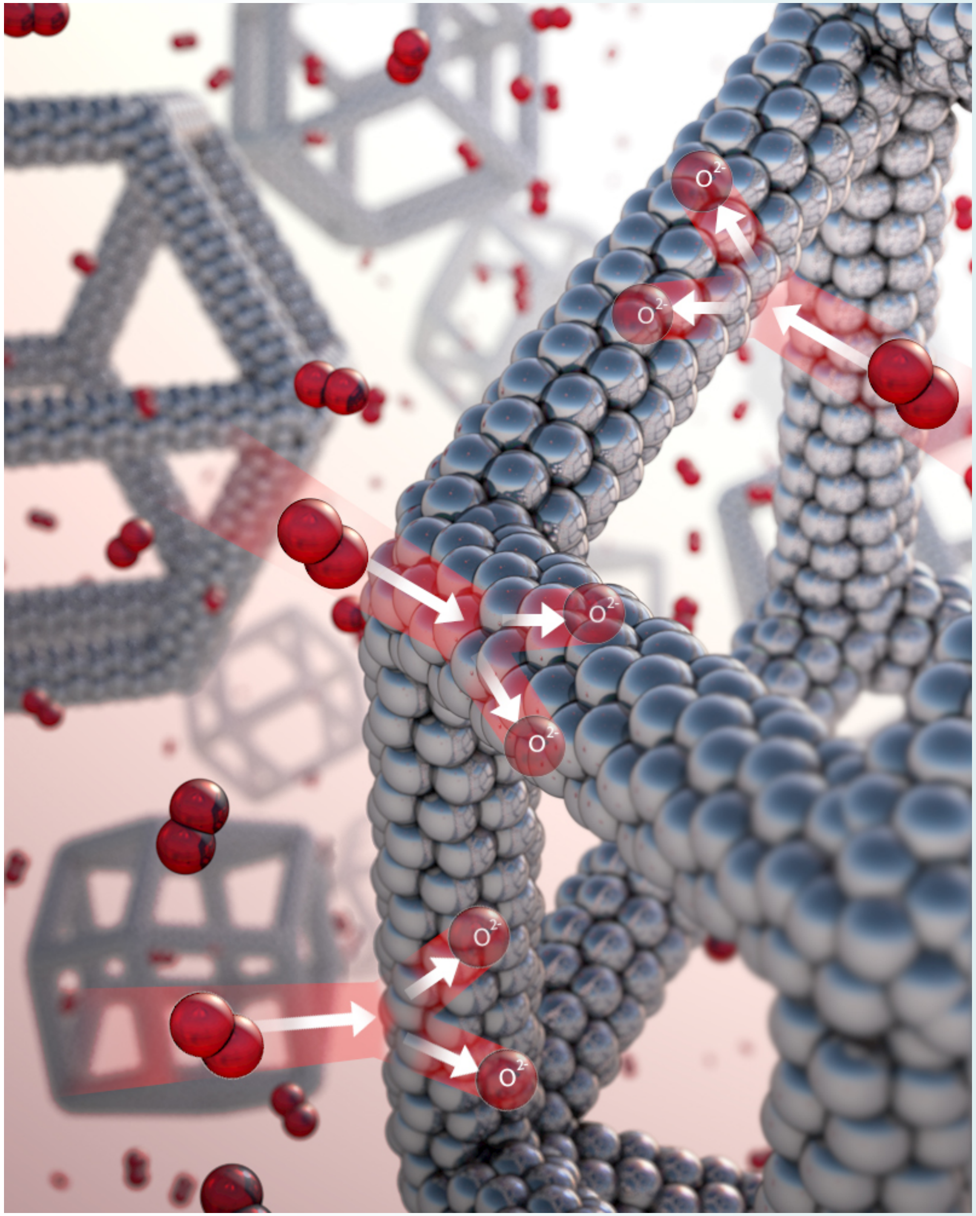
## *Electrochemical Evaluation of Nanoframes*

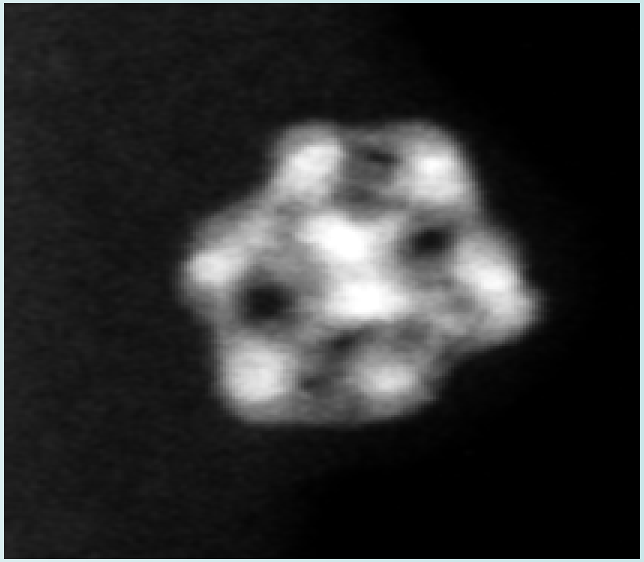


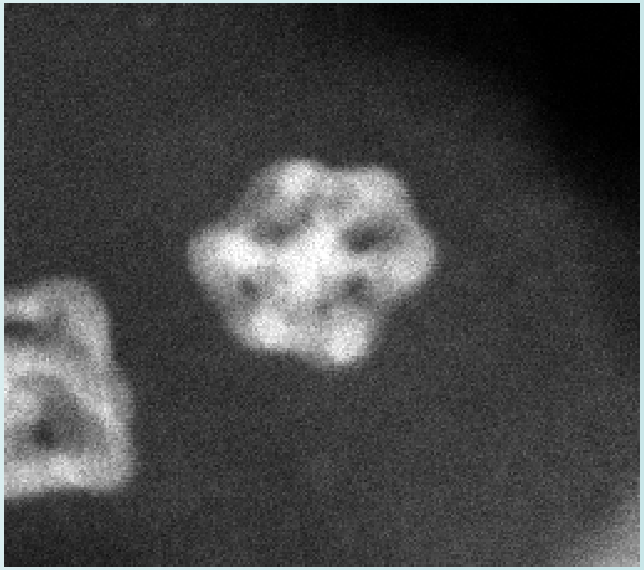




- No change in activity after 10K cycles 0.6 – 1.0 V
- Specific activity increase over 20-fold vs. Pt/C
- Mass activity increase over 35-fold vs. Pt/C
- Increase in mass activity over 15-fold vs. DOE target

## Accomplishments and Progress: *Nanoframes – Principle of Operations*

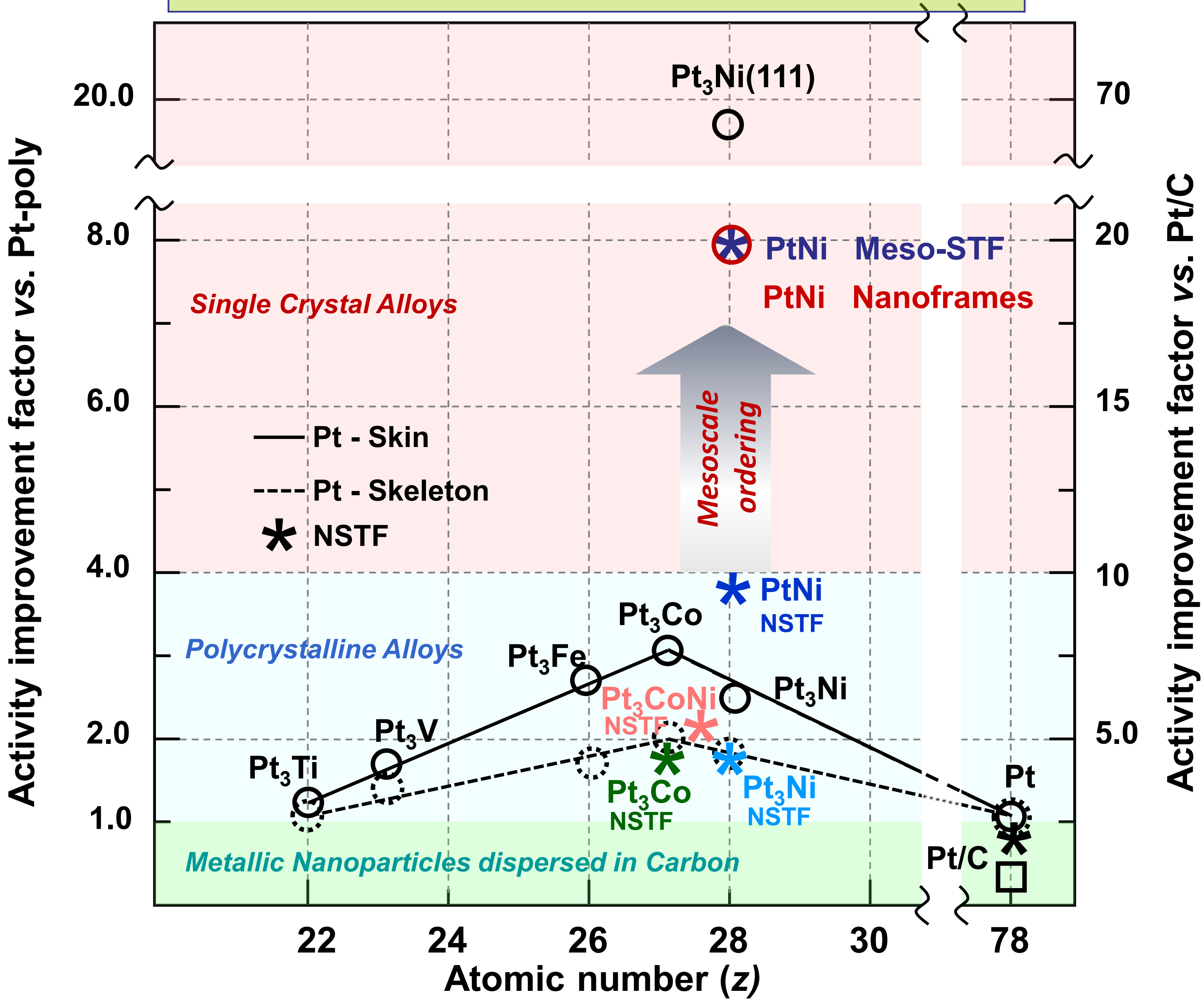




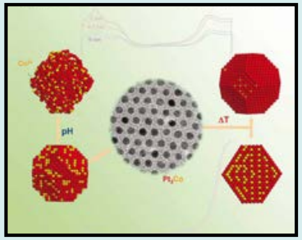
# Accomplishments and Progress: *ORR on Pt-alloys*

## *Electrochemical Activity Map for the ORR*



# Summary

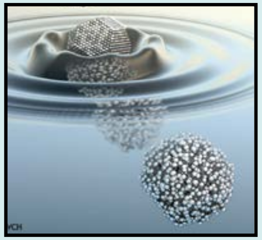
## Electrocatalysts based on nanosegregated Pt alloy NPs, NWs, MSTFs and Nanoframes



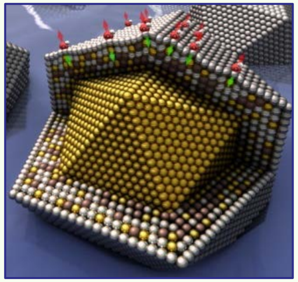
Efficient implantation of fundamental principles to the practical systems in the form of NPs, NWs, and nanoframes with adjustable compositional profile and structure

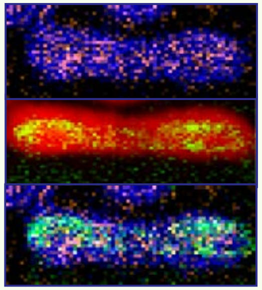
Established methodology that is capable to form and determine the nanosegregated Pt-skin surfaces for different classes of electrocatalysts

Established scalable synthetic protocols to produce larger amounts of materials



## Evaluation of multimetallic Pt-alloy electrocatalysts

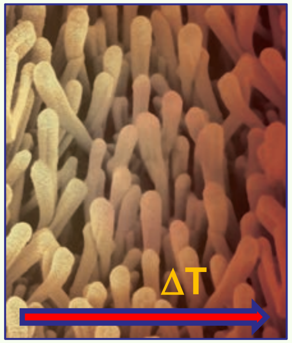




Different classes of materials have been synthesized in the form of NPs, NWs, nanoframes and characterized by TEM, HRSEM, in-situ HRTEM, XRD, RDE, MEA

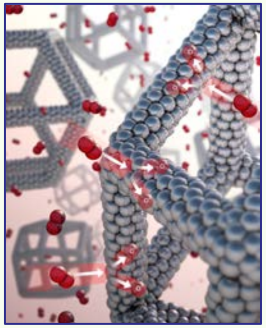
Specific activity of Pt-alloy vs. Pt/C electrocatalysts can be improved by 20-fold for Nanoframes and MSTF, 10-fold for core/shell NPs and 7-fold for NWs.
Mass activities improvements vs. Pt/C are 36-fold for nanoframes, 7-fold for core/shell, 6-fold for MSTF and 4-fold for NWs (RDE in 0.1M $HClO_4$ @ 0.95V *vs.* RHE)

Stability of Nanoframes, MSTF, core/shell NPs and NWs is superior compared to Pt/C




Two fold power of annealing facilitates the formation of an energetically more favorable surface state rich in (111) facets and distinct oscillatory segregation profile in core/shell NPs, NWs, mesostructured thin films and Nanoframes

Nanoframes are the first nanoscale catalyst with ORR bulk single crystal activity



# Future Work

### FY 2014

- Final tailoring of the composition that can provide activity/durability balance in Pt-alloys catalysts
- Synthesis and characterization of nanosegregated Pt-alloy nanoframe catalyst
- Optimization of the catalyst total metal loading
- Electrochemical evaluation of nanoframes in RDE and MEA (ANL, 3M)
- Scaling up of synthesis approach to produce larger quantities of the catalysts

### FY 2015

- Activity/stability evaluation and optimization of MEA protocols at 3M, GM and ANL
- Achieving full capacity for scaling up of chemical synthesis of nanoframes supported on HSA carbon
- Alternative approaches for fabrication of nanoframe catalysts with ultra low PM content

# Collaborations

**SUB-CONTRACTORS**

- **Oak Ridge National Laboratory** – HRTEM
- **Brown University** – Chemical Synthesis
- **University of Pittsburgh** (ex-Indiana University Purdue) – Theoretical Modeling
- **3M** – MEA Testing

**COLLABORATORS**

- **Argonne National Laboratory** – Nanoscale fabrication and DFT (CNM)
- **GM** – Technology transfer

# Publications and Presentations FY09-14

*14 Publications*
*32 Presentations*
*~650 Citations*
*2 issued US patents*
*3 patent applications*

**US 7,871,738 B2**
**Jan. 18, 2011**

(54) **NANOSEGREGATED SURFACES AS CATALYSTS FOR FUEL CELLS**

(75) Inventors: **Vojislav Stamenkovic**, Naperville, IL (US); **Nenad M. Markovic**, Hinsdale, IL (US)

(73) Assignee: **UChicago Argonne, LLC**, Chicago, IL (US)

**US 8,178,463 B2**
**May 15, 2012**

(54) **HIGHLY DURABLE NANOSCALE ELECTROCATALYST BASED ON CORE SHELL PARTICLES**

(75) Inventors: **Vojislav Stamenkovic**, Naperville, IL (US); **Nenad M. Markovic**, Hinsdale, IL (US); **Chao Wang**, Chicago, IL (US); **Hideo Daimon**, Osaka (JP); **Shouheng Sun**, Providence, RI (US)

(73) Assignee: **UChicago Argonne, LLC**, Chicago, IL (US)