Anodes-Nanoscale Heterostructures and Thermoplastic Resin Binders: Novel Li-ion Anode Systems

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Project ID #: ES061

Overview

- **Timeline**
  - Start: Jan 2011
  - Finish: December 2015
  - 100% complete
- **Budget**
  - Total project funding
    - $1, 082.7K
  - Funding received in FY11
    - $310.3K
  - Funding for FY12
    - $330.8K

- **Barriers**
  - **Low specific energy and energy density**
  - **Poor cycle life and coulombic efficiency**
  - **Poor rate capability**
- **Targets for PHEV (2015)**
  - ➢ **Available Energy: 3.5-11.6 kWh**
  - ➢ **Cycle life: 3,000-5,000 deep discharge**
  - ➢ **Recharge rate : 1.4-2.8 kW**
- **Partners/Collaborators/Students**
  - **Industries**
    - Ford Motor Company
  - **National Laboratory**
    - Dr. Robert Kostecki, LBNL
    - Dr. Vincent Battaglia, LBNL
  - **Other Universities**
    - Dr. Spandan Maiti, University of Pittsburgh
  - **Research Faculty/Students**
    - Dr. Moni Kanchan Datta, University of Pittsburgh
    - Rigved Epur, University of Pittsburgh

Objectives of this Study
May 2011-May 2012

- Identify new alternative nanostructured anode materials to replace synthetic graphite that will provide higher gravimetric and volumetric energy density
- Similar or lower irreversible loss (≤15%) in comparison to synthetic graphite
- Similar or better coulombic efficiency (≥99.9%) in comparison to synthetic graphite
- Similar or better cyclability and calendar life in comparison to synthetic graphite
- Investigate microcrystalline (μm-Si), nano-crystalline (*nc*-Si), nanoparticle (*np*-Si) and amorphous Si (*a*-Si) based nanocomposite anodes
- Improve the **specific capacity, available energy density, rate capability and cycle life** of nano-structured and amorphous Si based anode materials
- Identify ***elastomeric thermoplastic binders*** capable of binding the active materials preventing de-lamination

Milestones

Month/Year	Milestones or Go/No-Go Decision
July 2011	Milestone: Reduce Irreversible loss to **less then ~15% of** Si/C and Si/carbon nanotubes (CNT) nanocomposite anodes using **cost effective processing methods**
September 2011	Milestone: Improve the coulombic efficiency of Si/C and Si/CNT nanocomposite above 99.5%
December 2011	Milestone: Achieve Si/C and CNT/Si composite exhibiting low irreversible loss, high couloumbic efficiency, stable reversible capacity higher than **~1200mAh/g**
March 2011	Milestone: Characterize the hetero-structures for structure and composition using electron microscopy techniques such as, SEM, TEM and HREM
May 2011	Milestone: Identify suitable **elastomeric thermoplastic binders** for anode materials

Si: Silicon, **C**: Graphite or Carbon, **CNT**: Carbon nanotube

Approach

- Explore ***Si and carbon/CNT*** based nanocomposite anode
  - Explore ***novel low cost approaches*** to generate Si/C and Si/CNT composite comprising microcrystalline (μm-Si), nanocrystalline (*nc*-Si), nanoparticle (*np*-Si) or amorphous Si (*a*-Si) and a variety of carbon precursors:
    - ***High energy mechanical milling (HEMM)***
    - ***Chemical reduction followed by HEMM***
    - ***Chemical vapor deposition (CVD)***
    - ***Pulsed laser deposition (PLD)***
    - ***RF magnetron sputtering (RFMS)***
    - ***Fluidized bed reactor (FBR)***
- Explore **suitable surface control additives (SCA), interface control additives (ICA), and surface electron conducting additives (SECA)** in Si/C and Si/CNT nanocomposite which will ***reduce 1st cycle irreversible loss (IR) and improve the coulombic efficiency (CE)*** in subsequent cycles
  - Use of selective microstructure of graphite (e.g. **KS6, MCMB, SFG**) as matrix exhibiting low (< 20%) first cycle irreversible loss.
  - **Coating of Si/C composite** with suitable element or compound surface control additives (SCA) ***to improve CE and cycling stability***.
  - Use of highly **conductive additives to improve CE**.
- Explore high strength, high ductility ***elastomeric thermoplastic binders*** to bind the active materials
- Full cell and long cycling tests:
  - ***Coin cell and pouch cell*** configuration with suitable cathode

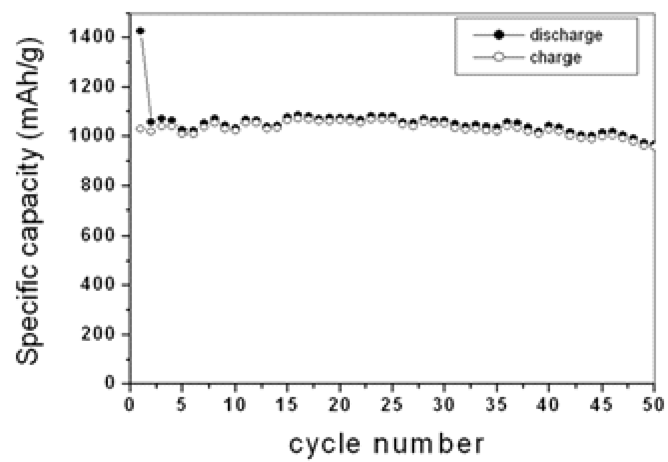
Technical Accomplishments (FY-11)
Problems with Si/Graphite Nanocomposite
<u>1st cycle Irreversible loss and Coulombic efficiency</u>

In FY-10, **Si/C nanocomposite** synthesized by **HEMM** using **PAN as interface reaction barrier**

<u>Si microstructures used in FY-10</u>:
- microcrystalline (≤44μm)
- amorphous (*a*-Si)
- nanocrystalline (*nc*-Si) (~10-20nm)
- nanoparticles (*np*-Si) (~50-100nm)

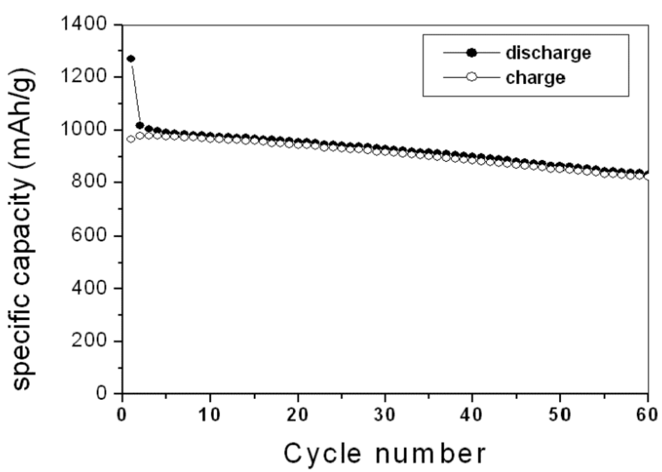
<u>Carbon source used in FY-10</u>:
- ❑ ***Graphite flake (1-2μm, Aldrich)***
- ❑ ***PAN based carbon***

Si/C composite with *a*-Si and graphite flake



Cycled at 160mA/g (C/6), 0.02V-1.2V
Loss per cycle: **0.09%**, CE: **99.2**%, **<u>IR: 37%</u>**

<u>Si/C composite with **μm-Si and graphite flake**</u>



Cycled at 160mA/g (C/6), 0.02V-1.2V,
Loss per cycle: 0.2%, CE: **99.2%, <u>IR: 30%</u>**

Si/C nanocomposite synthesized by HEMM, studied in FY-10, within a wide range of composition shows:

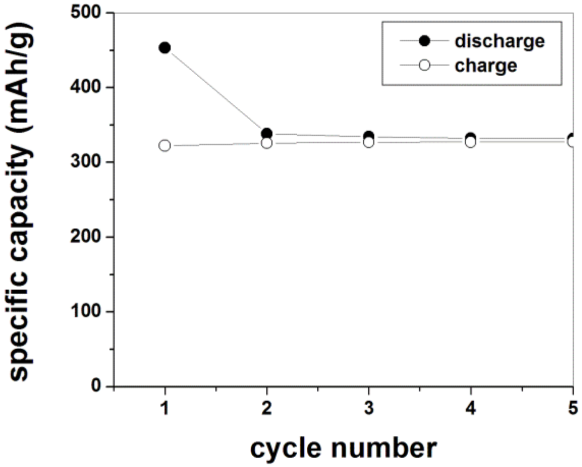
<u>Advantage:</u>
- ➢High reversible capacity: **700-1200mAh/g**
- ➢Excellent cyclability: **0.01-0.2% loss per cycle**

<u>Disadvantage:</u>
- ❑**Large irreversible loss: ≥30%**
- ❑**Low coulombic efficiency: ≤99.5%**

Technical Accomplishments (FY-11)

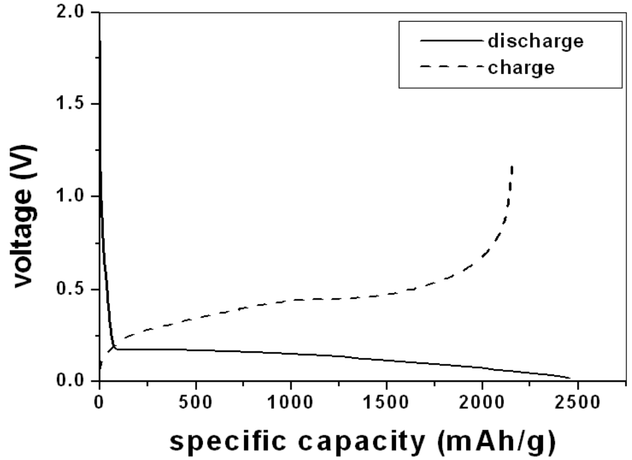
Probable cause of 1st cycle irreversible loss of Si/C Nanocomposite

Electrochemical properties of *Graphite flake* (Aldrich) used in FY-10



Cycled at 100mA/g (C/3.2), 0.02V-1.2V
Drawback:
➢Large IR loss: ~**28-35%**

Electrochemical properties of *a*-Si, *np*-Si, *nc*-Si used in FY-10



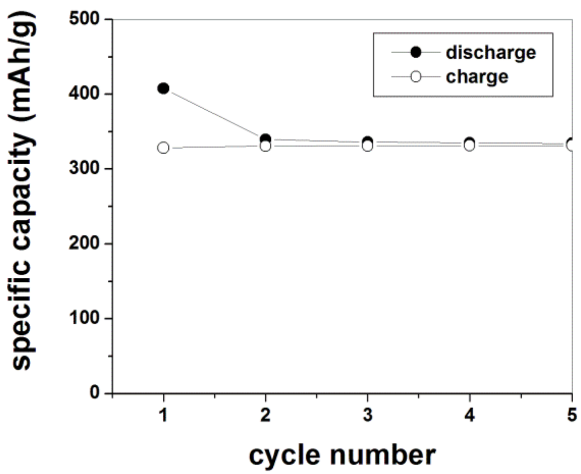
Cycled at 160mA/g, C/15, 0.02V-1.2V
***a*-Si** synthesized by thermal cracking of Si based precursor
➢Irreversible loss: **12%**
➢*a*-Si, *nc*-Si and *np*-Si shows: **~5-15% irreversible loss (supplemental slides)**

- **Si/Graphite flake nanocomposite studied in FY10**
  - ***Large first cycle irreversible loss (>30%)*** arising due to **carbon matrix (graphite flake and PAN-C)**
  - ***Low coulombic efficiency (<99.5%)***
- **Major challenge/Target**
  - Irreversible loss reduction **(≤15%)**
  - Improve the coulombic efficiency **(≥99.9%)**
- **Concepts**
  - **Reduce the SEI layer formation** which may arise due to the presence of graphite flake and PAN-C
  - Increase **electronic conductivity** to improve the coulombic efficiency **using (SECA)**
  - Improve the IR, CE and stability of Si/C composite **using SCA**

Technical Accomplishments (FY-11)
Reduction of 1st cycle irreversible loss of Si/C composite

Use of ***low first cycle irreversible loss based synthetic graphite as matrix***

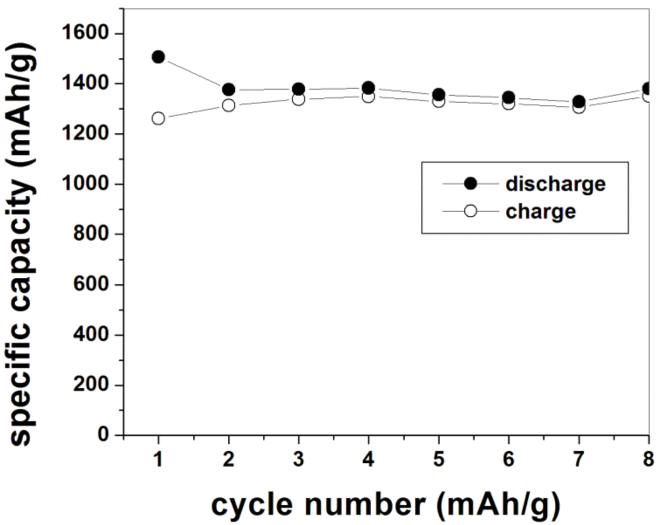
Electrochemical properties of synthetic graphite (**MCMB, KS6**)



Cycled at 100mA/g (C/3.2), 0.02V-1.2V
- Excellent coulombic efficiency and stability
- **Low first cycle irreversible loss: 15-20%**

Target:
synthesis of Si/C composite **using KS6/MCMB** graphite as a matrix

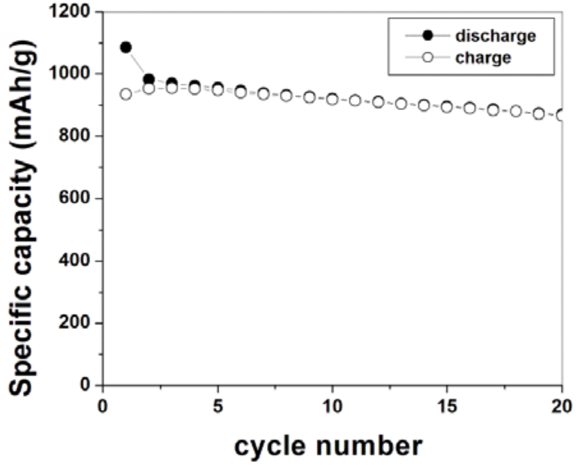
KS6/*np*-Si nanocomposite synthesized by HEMM



Cycled at 160mA/g, 0.02V-1.2V
- Low first cycle *irreversible loss: 20%*
- Low irreversible loss due to presence **KS6 graphite as matrix**
- Couloumbic efficiency: ~99.2%
- Excellent stability: 0.01% loss per cycle

Major challenge: improve the **coulombic efficiency of KS6/Si** **above 99.9%**

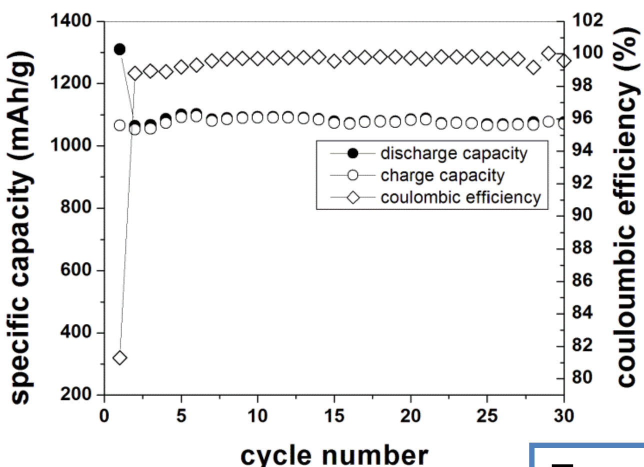
Technical Accomplishments (FY-11)
Improve the coulombic efficiency of Si/C nanocomposite using surface electron conducting additives (SECA)



μm-Si/KS6/SECA nanocomposite with **microcrystalline Si**:
Cycled at 160mA/g, 0.02V-1.2V

- Irreversible loss: **14%**
- Coulombic efficiency: **99.8%**
- Loss per cycle: 0.3%
- **KS6/Si/SCA improve the coulombic efficiency while maintaining low 1st cycle irreversible loss**

Target: ***improve the cyclability while maintaining low first cycle irreversible loss and high coulombic efficiency*** **using *a*-Si or *np*-Si**



a-Si/KS6/SECA based composite
Cycled at 160 mA/g, C/6.5, 0.02V-1.2V

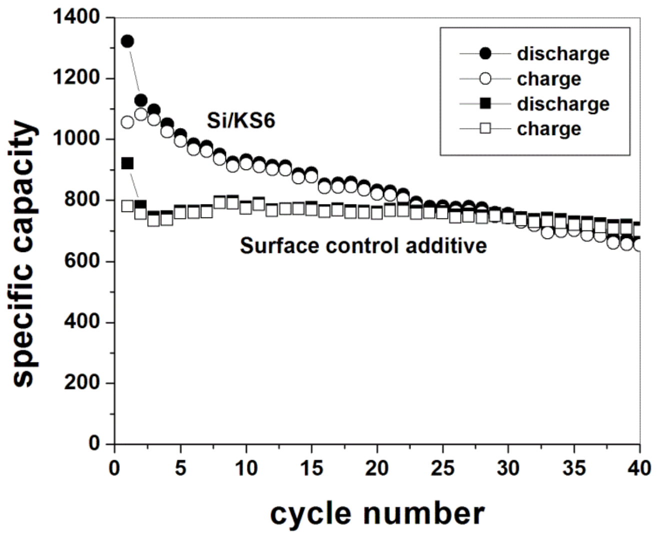
- Reversible capacity: **~1050mAh/g**
- Fade in capacity: **0.04%** per cycle
- First cycle Irrversible loss:~ **17%**
- Coulombic efficiency: **99.8%**

Identify and engineer a Si/C nanocomposite structure which shows high specific capacity with low IR, high CE and excellent cyclability

Target for FY-12: Long cycle life ≥300 cy. and tested in full cell configuration

Technical Accomplishments (FY-11)
Improve the CE, IR and stability of Si/C nanocomposite using surface control additives (SCA)

Target:
Improve the stability of **μm-Si/KS6 composite using surface control additives (SCA)**



μm-Si/KS6 nanocomposite **without SCA**
Cycled at 160mA/g, 0.02V-1.2V
1st discharge: ~1317mAh/g, 1st charge: ~1131mAh/g
- Irreversible loss: **14%**
- Coulombic efficiency: **99.1%**
- Loss per cycle: 1%

μm-Si/KS6 nanocomposite **with SCA**
Cycled at 160mA/g, C/5, 0.02V-1.2V
1st discharge: ~923mAh/g, 1st charge: ~798mAh/g
- Irreversible loss: **13.5%**
- Coulombic efficiency: **99.8%**
- Loss per cycle: 0.1%

Surface control additive improve the stability while maintaining the IR and CE

Target for FY-12: Proper design and precise surface control to achieve high specific capacity with low IR and CE

Technical Accomplishments (FY-11)

Formation of amorphous or nanocrystalline Si (*a*-Si/nc-Si) by chemical reduction of silicon precursors

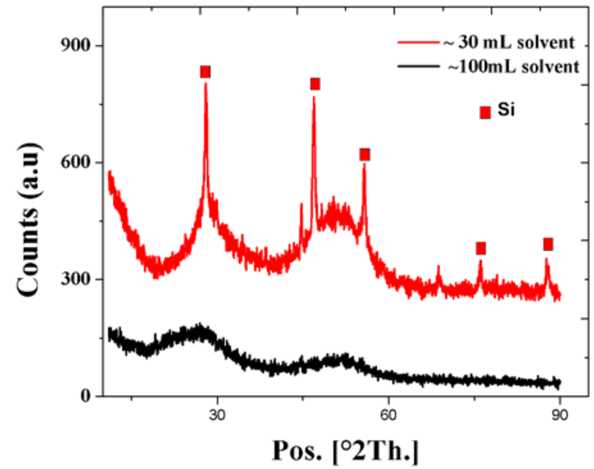
$$SiX_4 + 4\,Li \rightarrow Si + 4\,LiX$$

Heat Li metal to 150°C in solvent with flowing Ar gas

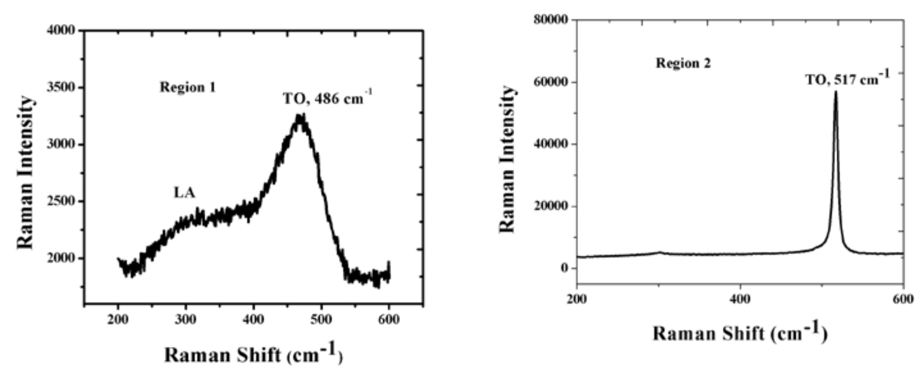
Add required amount of Si-precursors in controlled fashion

Product is centrifuged in anhydrous methanol to remove Li-complex and vacuum dried to give mix of a-Si & nc-Si

The above product is milled with graphite (Aldrich) +PAN and decomposed at 500°C to form a-Si/nc-Si/G/PAN-C composite

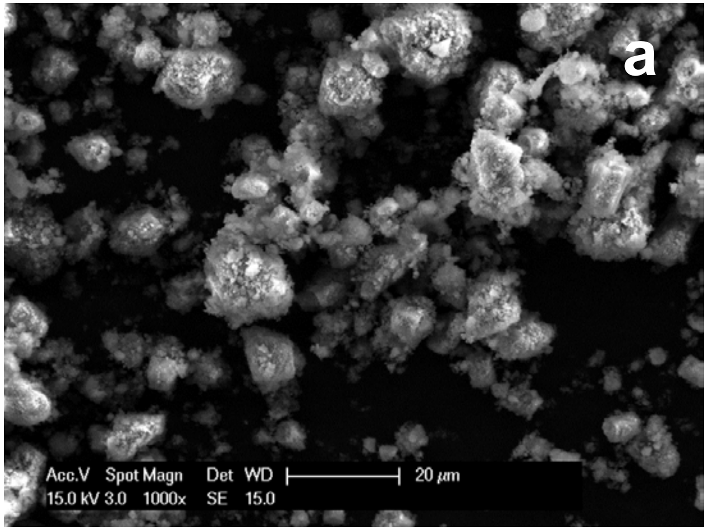


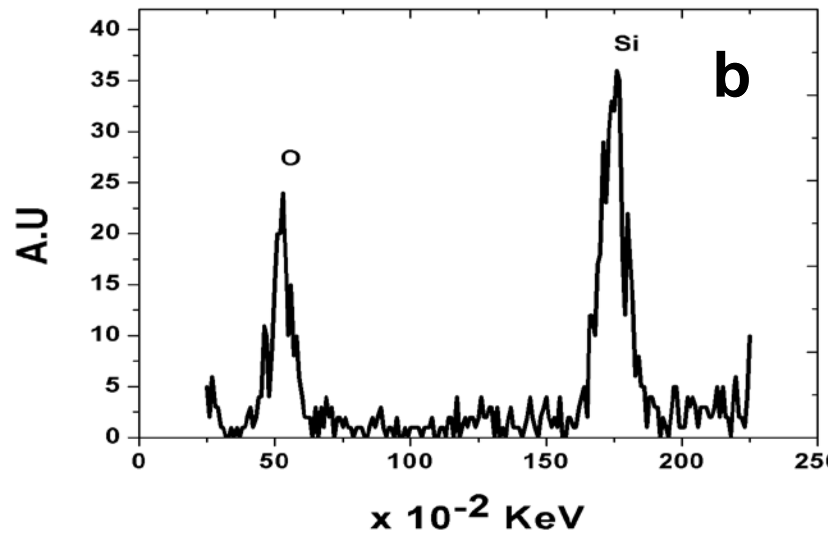
XRD anaysis showing effect of solvent on crystallinity of Si

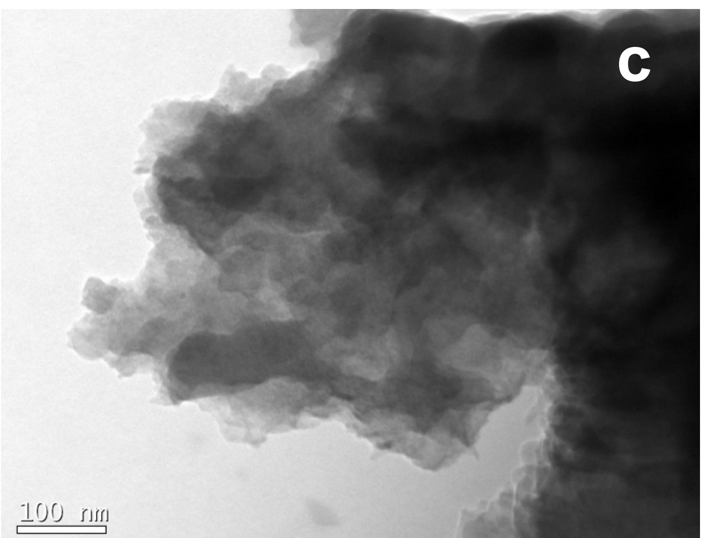


- Raman spectra obtained at 2 different regions of the obtained Silicon product confirming *a*-Si and nc-Si.

Technical Accomplishments (FY-11)
a-Si/nc-Si by chemical reduction of silicon precursors





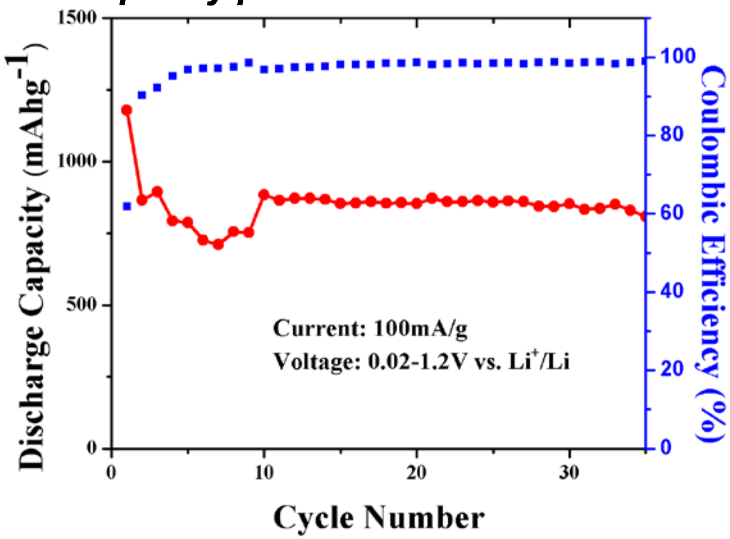


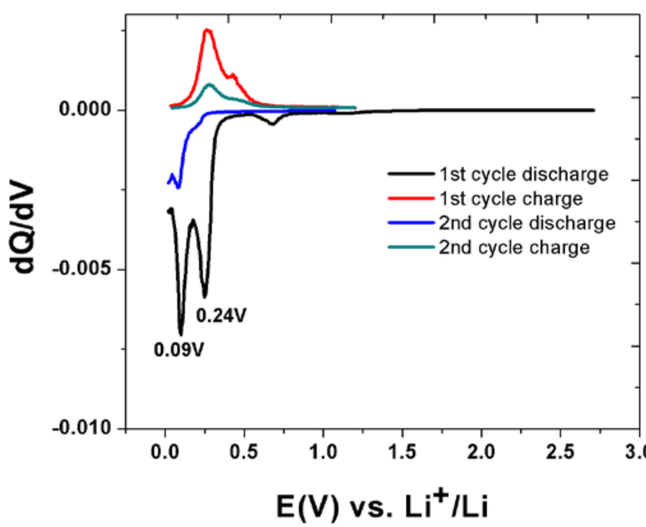
(a) SEM (b) EDAX & (c) TEM image of the *nc/a*-Si obtained after vacuum drying. EDAX shows presence of Si and O.

Technical Accomplishments (FY-11)

(*a*-Si/nc-Si/G-PAN-C) compsoite synthesized by chemical reduction of silicon precursors followed by HEMM

Capacity plot of a-Si/nc-Si/G/PAN-C





Cycled at : 100 mA/g, Voltage: 0.02 – 1.2 V vs. Li^+/Li

- First discharge capacity **~ 1180 mAh/g**
- First cycle irreversible loss: ~ 38%
- Possible reasons for IR loss :
  - Surface oxide (SiO_x)
  - SEI layer formation

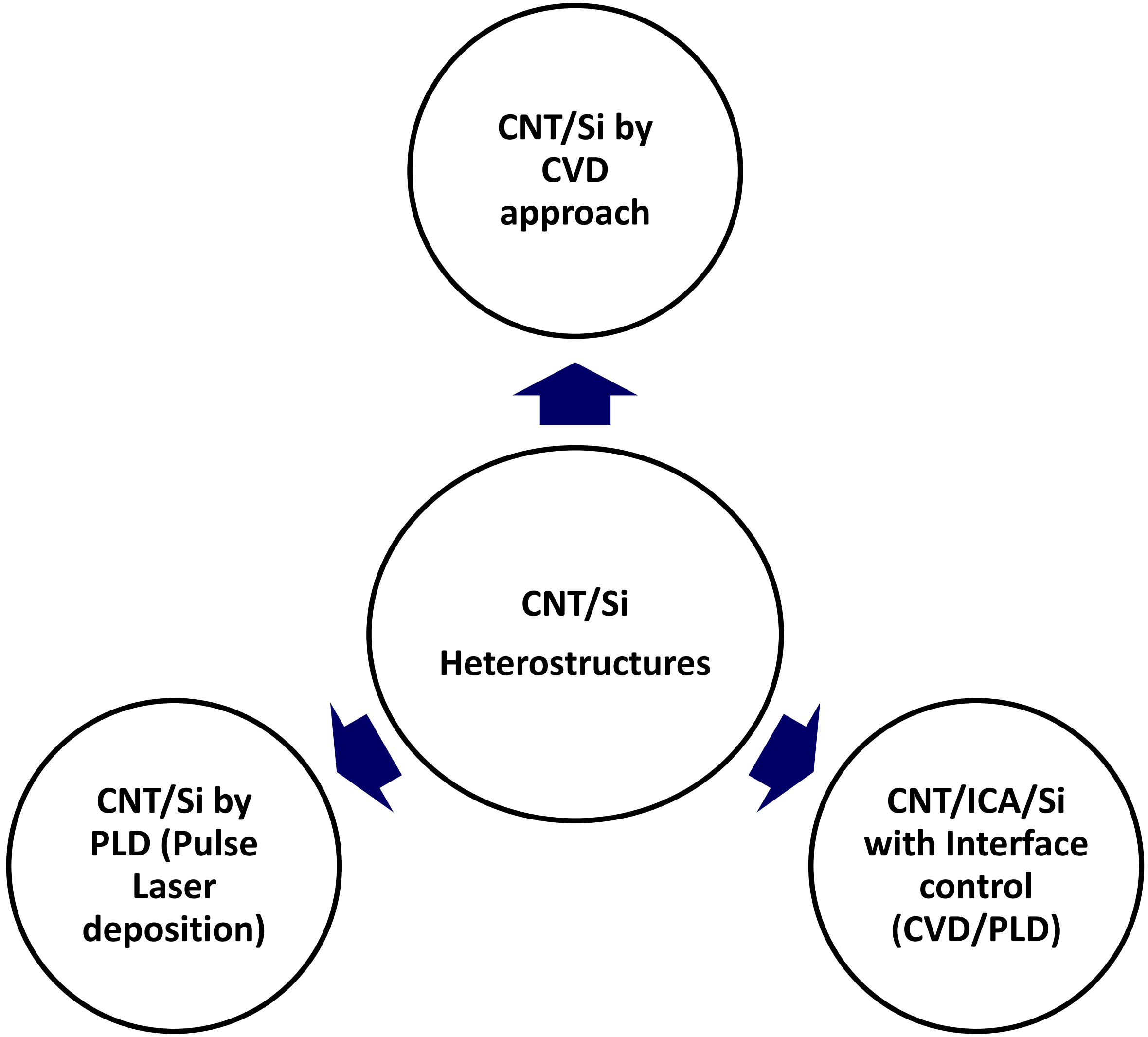
- Lithiation (1st cycle):
  - 0.24V : P(I)→P(II)
  - 0.09V: P(II) → P(III)
- Lithiation (2nd and subsequent cycles):
  - 0.24V: P(I)→P(II)
  - 0.09V: P(II)→P(III)
- Delithiation
  - 0.3V: P(III)→P(II)
  - 0.45V: P(II)→P(I) for all cycles

Composition:
PI: Li-50at.% Si (LiSi), PII: Li-30at.% Si (Li_7Si_3), PIII: Li-24at.% Si ($Li_{3.16}Si$)

Target at FY-12: *Reduce the IR ≤15% and CE ≥99.9%*

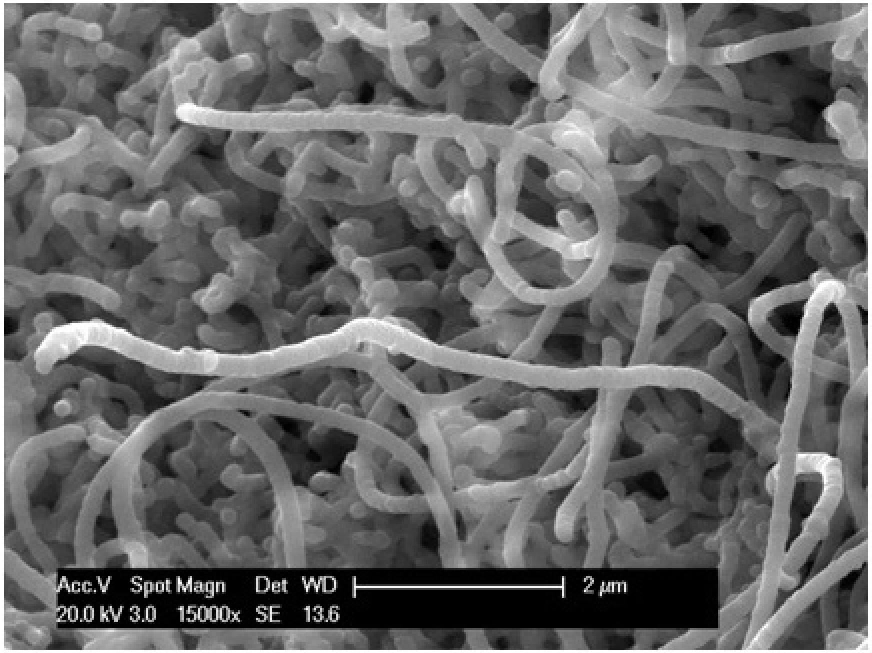
Wang et al., 2011, Elec. Comm , 13, 429
Datta et al., 2009 , J. Power Sources, 194, 1043

Technical accomplishments (FY-11)
Novel Synthesis of *nc*-Si/CNT composite anodes using Interface Control Additives (ICA)

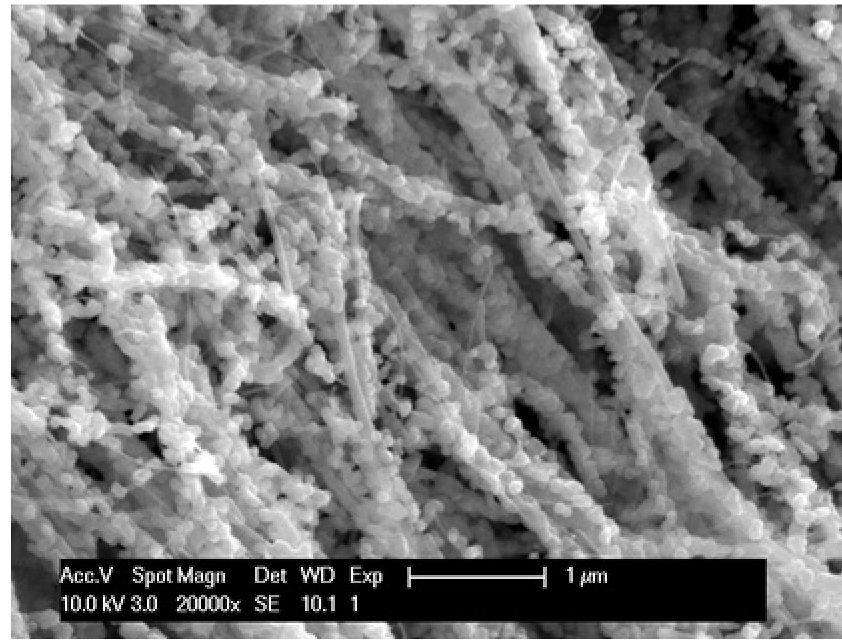


Technical accomplishments (FY-11)

Structural analysis of *nc*-Si/CNT Heterostructures by CVD



Silicon coated as uniform film on CNTs

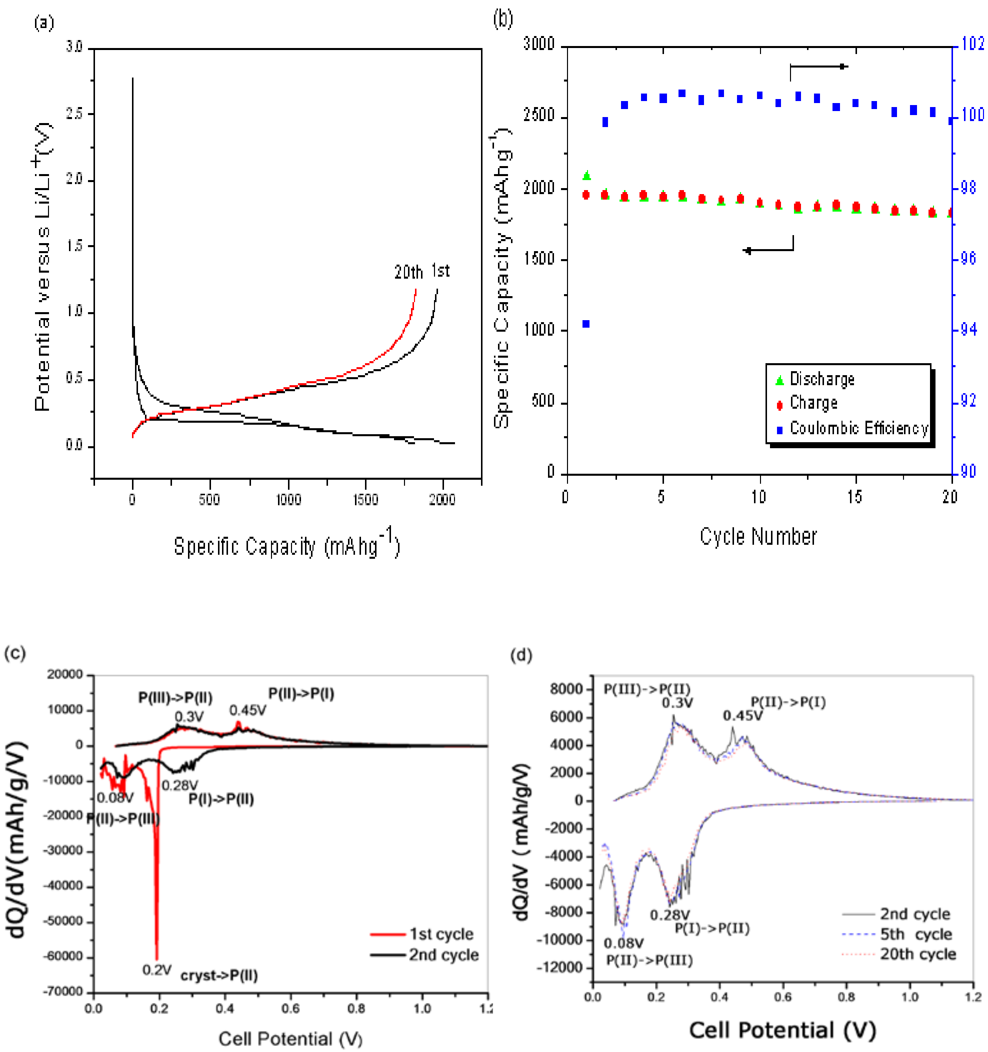


Silicon coated as film droplets at uniform spacing on CNTs

- **Film** – Higher partial pressure of SiH_4 (SiH_4:Ar=1:10)
- **Droplet** – Lower partial pressure of SiH_4 (SiH_4:Ar=1:30)
- **Size of silicon droplets** : 40-60 µm

Wang et al., 2011, Elec. Comm , 13, 429
Wang et al., 2010, ACS Nano, 4, 2233

Technical accomplishments (FY-11)
Electrochemical behavior of different morphologies of Si on MWCNTs (grown on Inconel 600 alloy)



Cycled at 100mA/g, 0.02V-1.2V

- 1st discharge specific capacity **~2078mAh/g**
- 1st charge capacity **~1958mAh/g**
- Irreversible loss : **~6% and excellent coulombic efficiency (~99.5%)**
- Lithiation (1st cycle):
  - 0.20V : Lithiation of *a*-Si to form Li_xSi alloys
  - 0.08V: P(II) → P(III)
- Lithiation (2nd, 5th and 20th cycles):
  - 0.28V: P(I)→P(II)
  - 0.08V: P(II)→P(III)
- Delithiation
  - 0.3V: P(III)→P(II)
  - 0.45V: P(II)→P(I) for all cycles

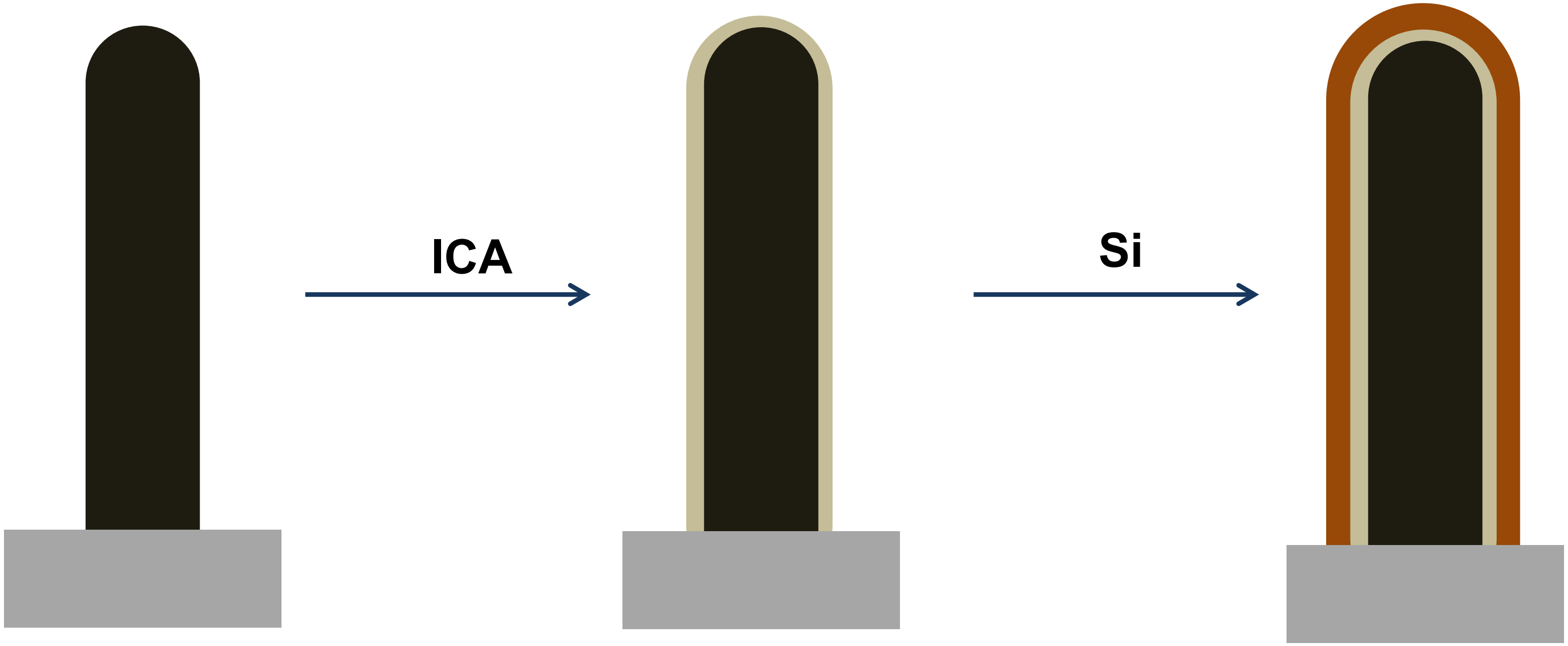
*No need of conductive polymer additive in the preparation process : "**Binder-Free**" approach*

Composition:
PI: Li-50at.% Si (LiSi), PII: Li-30at.% Si (Li_7Si_3), PIII: Li-24at.% Si ($Li_{3.16}Si$)

Datta et al., 2009, J. Power sources, 194 , 1043
Wang et al., 2011, Elec. Comm , 13, 429
Wang et al., 2010, ACS Nano, 4, 2233

Technical accomplishments (FY-11)
CNT/Si/ICA – Interface Control

ICA – Interface control additives

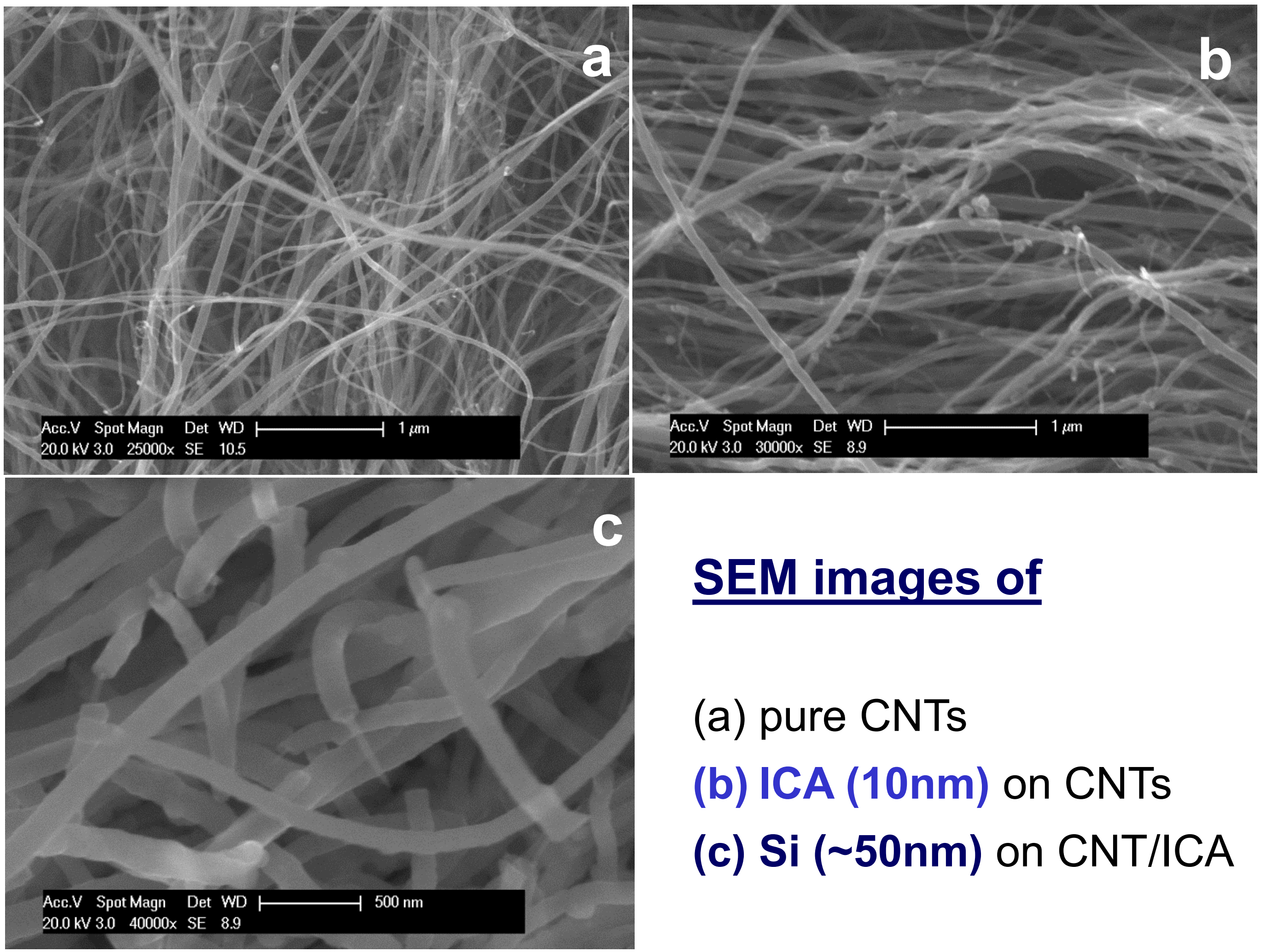


CNTs by CVD of m-xylene on quartz

ICA deposition by eBeam

Si by CVD of SiH_4

Technical accomplishments (FY-11)
CNT/Si/ICA heterostructures



SEM images of

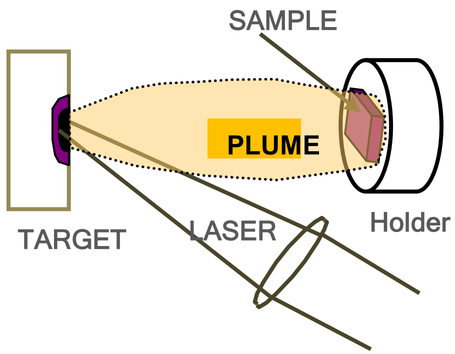
(a) pure CNTs

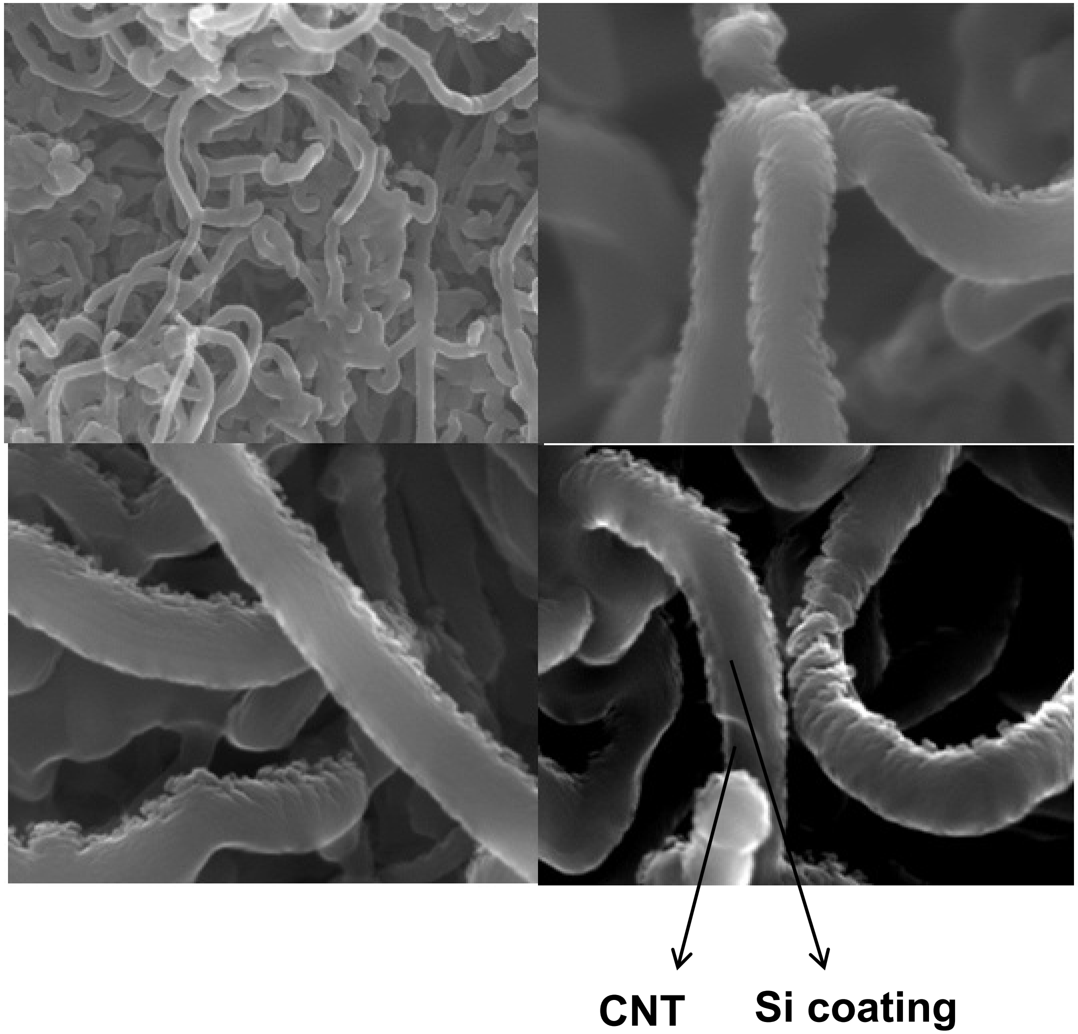
(b) ICA (10nm) on CNTs

(c) Si (~50nm) on CNT/ICA

Technical Accomplishments (FY-11)

Synthesis of CNT/Si by Pulsed laser deposition

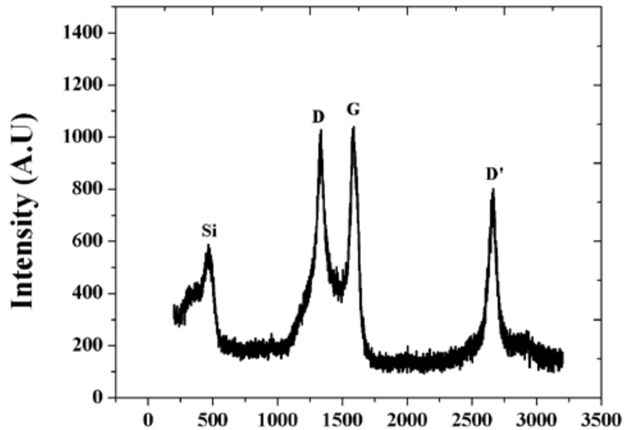


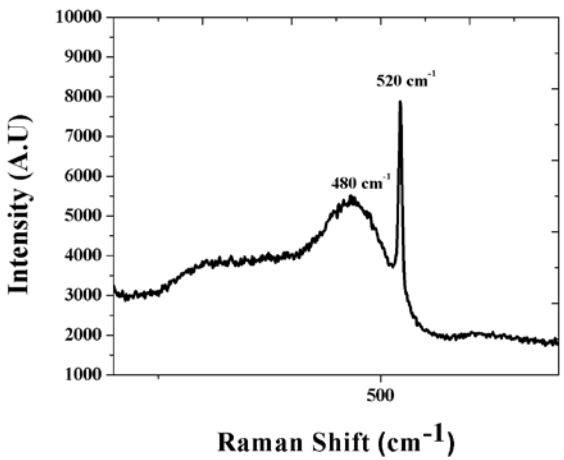


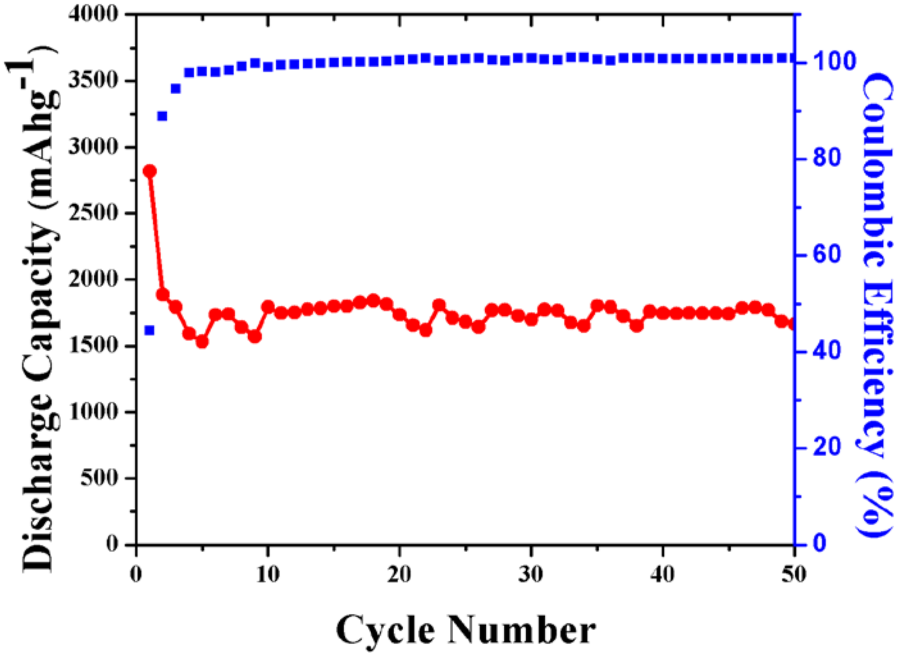
- E = 10 to 150 eV
- KrF excimer laser operating at 248 nm with pulse duration of 25ns, 600 mJ/pulse , and maximum 50 Hz repetition rate
- Non steady-state atom concentrations

Silicon thickness: 15-20 nm

Technical Accomplishments (FY-11)
CNT/Si by Pulsed laser deposition







Cycled at :100 mA/g , Voltage: 0.02-1.2 V vs. Li^+/Li

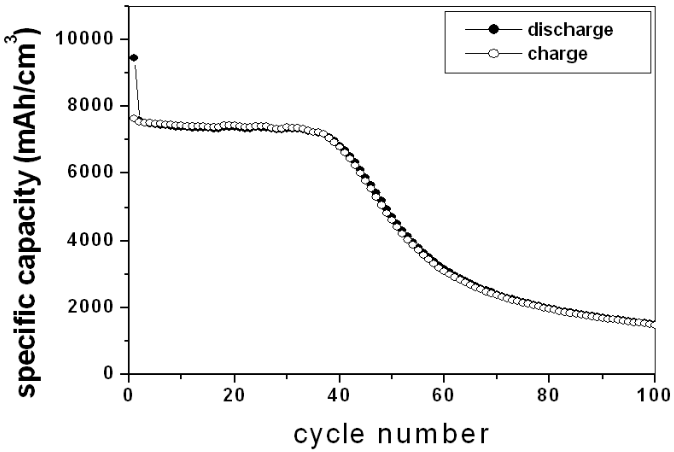
- Reversible capacity: ~**1500mAh/g with 99.8% CE**
- Capacities calculated based on silicon weight of the composite

- *Raman spectra shows the presence of CNTs (D' band) with I_g/I_d ~ 1*
- *Presence of both* **amorphous and crystalline phases of Silicon**

Target for FY-12: Optimize the process control to *reduce the IR ≤15% and CE ≥99.9%*

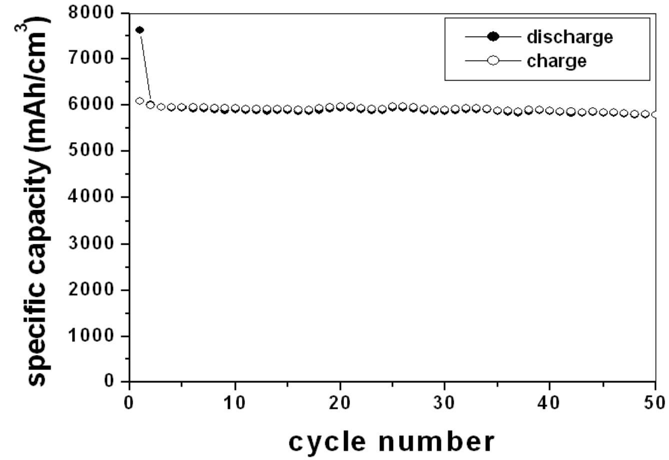
Technical Accomplishments (FY-11)
Synthesis of *a*-Si/C by RF magnetron sputtering

Thin film *a*-Si



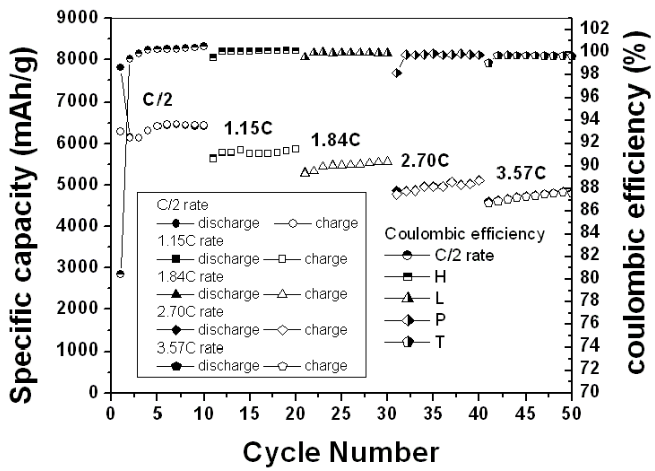
Cycled at 100μA/cm^2, C/2, 0.02V-1.2V
Specific capacity: **7080 mAh/cm^3 (~2820mAh/g)**

Thin film *a*-C/Si



Cycled at 100μA/cm^2, C/2.5, 0.02V-1.2V
Specific capacity: **6350 mAh/cm^3 (~2500mAh/g)**

Thin film *a*-C/Si, cycled at C/2-3.6C



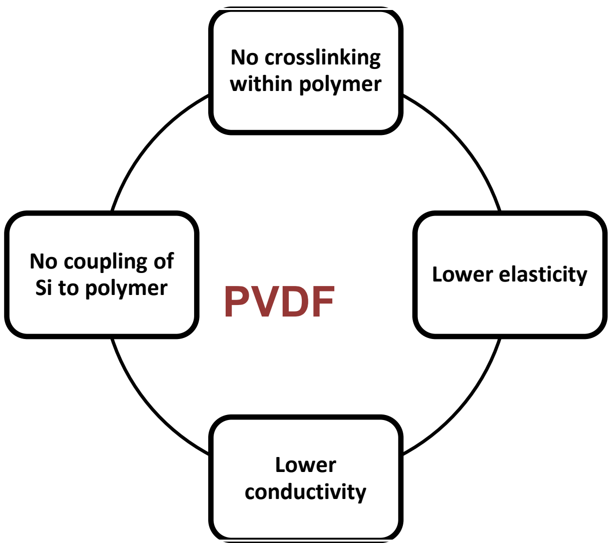
Thin film *a*-Si and *a*-Si/C film

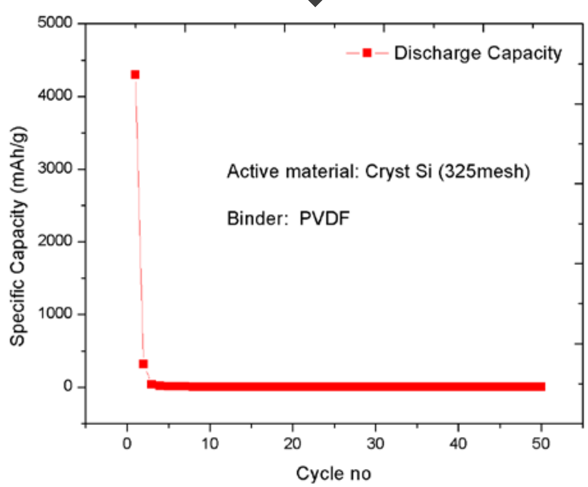
Synthesized by RFMS

- Low irreversible loss **(~20%)**
- **a-Si shows excellent cyclability (0.11% loss per cycle) and columbic efficiency (~99.8%) up to 30 cycles**
- **Improve the stability of *a*-Si/C thin film in comparison to *a*-Si film beyond 30 cycle (0.09% loss per cycle)**
- **Excellent rate capability up to 3.5C**

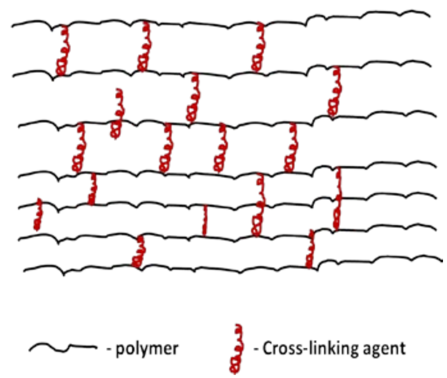
Datta et. al., Elec. Acta., 2011, 56, 4717

Technical Accomplishments (FY-11)
Development of higher fracture strength thermoplastic binder

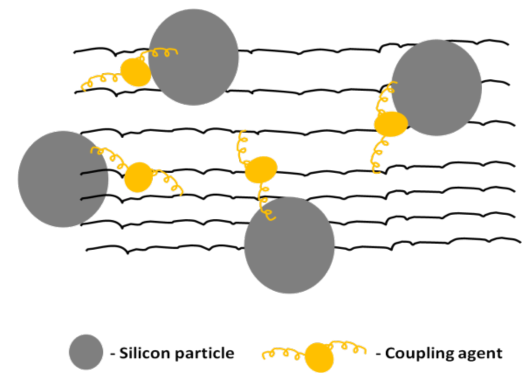




Approach



Cross-linking

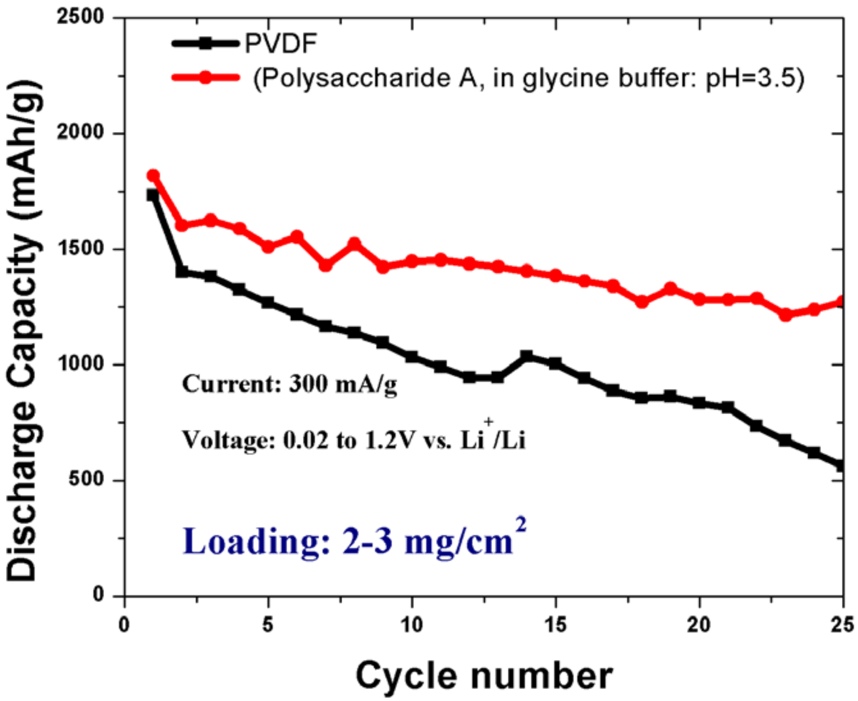


Coupling

Properties :

- Higher fracture strength of the binder
- Better elasticity and conductivity
- **Crosslinking and coupling agents** to enhance binding capacity

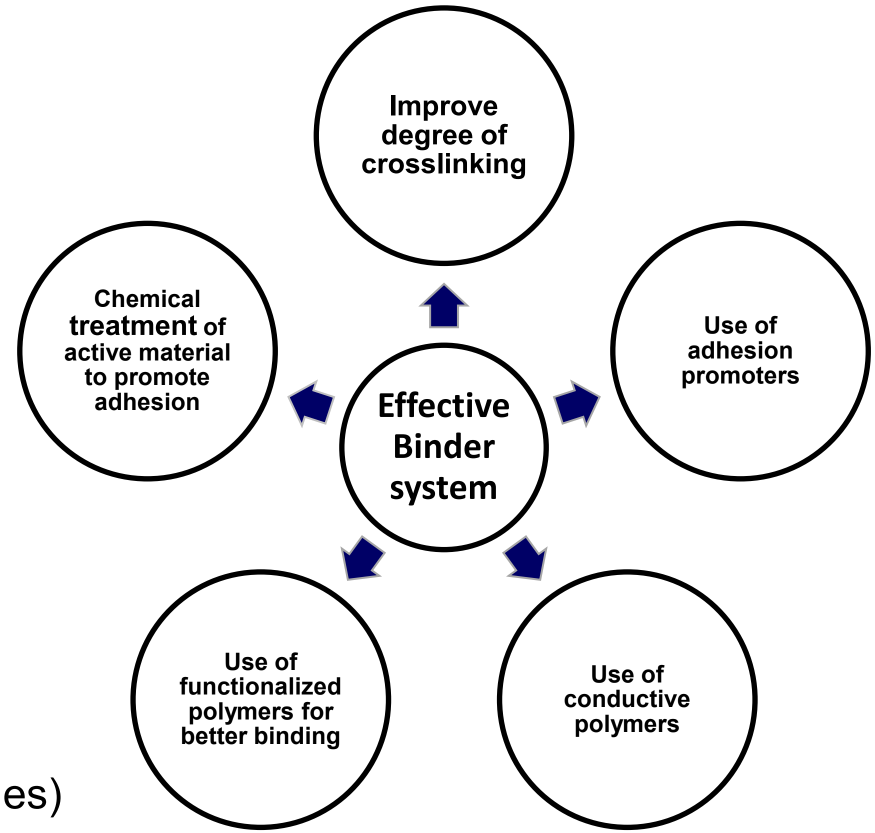
Technical Accomplishments (FY-11)
Development of higher fracture strength thermoplastic binder



Cycled at 300mA/g, 0.02V-1.2V

- Better adhesion of Silicon with polymer
- High capacity retention (>1000mAh/g by 30 cycles)
- Better cyclability
- Loading of active materials: **2-3mg/cm^2**
- Preliminary results indicate promise of novel binder

Direction of Approach



Collaborations

Industry

- Ford Motor company (A. Drews, T. Miller)

National Laboratory:

- LBNL (Vince Bhattaglia); ANL (Chris Johnson), NREL (Dillon); PNNL (J. Liu, C. Wang)

University*:

- University of Pittsburgh (S. Maiti)
- Pennsylvania State University (D. Wang)

*Collaborators within the VT Program

Activities for next fiscal year

- Synthesize nanostructured and amorphous Si based anode by cost effective methods and identify new binders to achieve stable ***reversible capacity (~1200mAh/g***) with low **irreversible loss (≤ 15%)** and high **coulombic efficiency (≥99.9%)** in full cell configurations.
- Identify interface control additives (ICA) to minimize first cycle irreversible loss and improve coulombic efficiency in hierarchical nano-scale structures.
- Identify novel SECA and SCA to achieve IR of ~15% and CE ~99.9% in HEMM derived systems.
- ***Novel thermoplastic binders*** with better coupling to active material resulting in improved cyclability.
- Coin cell and pouch cell configuration with suitable cathode.

Summary

- Approaches to generate scaled up quantities of high performance amorphous Si (*a*-Si) and nanocrystalline Si (*nc*-Si) indicate promising electrochemical response.
  - Results on HEMM and CVD derived composites indicate capacities in the 1000 mAh/g – 2000 mAh/g range.
  - low irreversible loss (~5-18%) have been achieved.
  - Excellent coulombic efficiency (~99.5-99.8%) has been attained.
  - Binderless concept of VASCNT exhibit capacities ~1400-2000 mAh/g.
- Use of ICA, SECA and SCA are useful for lowering first cycle irreversible loss, improving the coulombic efficiency and cyclability as well as rate capability.
- Project initiated on generation of novel thermoplastic binders.
  - Initial results indicate improvements compared to PVDF.

List of Publications and Presentations

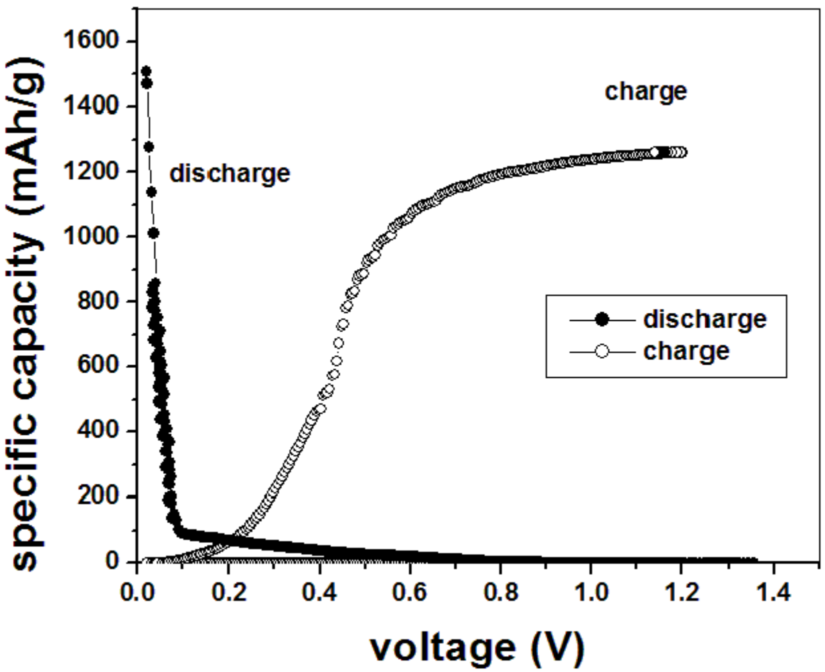
- **Publications**
  - M. K. Datta, J. Maranchi, S. J. Chung, R. Epur, K. Kadakia, P. Jampani, and P. N. Kumta, “Amorphous silicon-carbon based nano-scale thin film anode materials for Li-ion batteries”, Electrochimica Acta 56 (2011) 4717-4723.
  - Wei Wang, R. Epur, and P.N. Kumta, “Vertically Aligned Silicon/Carbon Nanotube (VASCNT) Arrays: Hierarchical Anodes for Lithium-ion Battery”, Electrochemistry Communications 13 (2011) 429-432.
  - Wei Wang and P. N. Kumta, “Nanostructured Hybrid Silicon/Carbon nanotube heterostructure: Reversible high capacity lithium ion anodes” ACS NANO 4 (2010) 2233-2241.
  - M. K. Datta and P. N. Kumta, “In situ electrochemical synthesis of lithiated Silicon-Carbon based composite anode Materials for Lithium Ion Batteries”, J. Power Sources 194 (2009) 1043.
  - R. Teki, M. K. Datta, R. Krishnan, T. C. Parker, T. M. Lu, P. N. Kumta and N. Koratkar, “Nanostructured Si anodes for Lithium ion rechargable batteries”, Small 5(2009) 2236.
  - J. Nanda, M. K. Datta, J. T. Remillard, A. O’Neil and P. N. Kumta, “In-situ Raman microscopy during discharge of high capacity silicon-carbon composite Li-ion battery negative electrode” Electrochemistry Communication, 11 (2009) 235-237.
  - M. K. Datta and P. N. Kumta, “Alloying/dealloying behavior of Li-ion with Si during electrochemical reaction”, in preparation.
  - R. Epur, M. Ramanathan, F.R. Beck, A. Manivannan, P. N. Kumta, “Electrodeposition of Amorphous Silicon Anode for Lithium Ion Batteries”, Mat Sci & Engg: B (2012) In Press
  - M. K. Datta, P. N. Kumta, “Si/C composite anode with surface control agent”, J. Power Sources, Under preparation,
  - M. K. Datta, P. N. Kumta, “Si/C composite anode with addition of electronic conducting agents”, Electrochimica Acta, Under preparation.

- **Presentations**
  - M. K. Datta nd P. N. Kumta, “Alloy design for long term cyclability of Si based anode materials for lithium ion batteries”, Society of Automotive Engineers, 2007 – Oral presentation.
  - R. Epur, S.J. Chung, M. Datta, A. Manivannan and P.N. Kumta, “Engineering Novel Si-CNT Heterostructures” MRS meeting, Boston (2011) - Oral presentation.
  - R. Epur, S. J. Chung, R. Kuruba, A. Manivannan and P. N. Kumta, “Nanocrystalline-Amorphous silicon composite anode by chemical reduction of silicon halides”, 220th ECS meeting at Boston, MA - Oral presentation
  - R. Epur, M. K. Datta, A. Manivannan & P. N. Kumta, “Nanocrystalline Silicon/Graphite/MWCNT based Heterostructured Electrodes - High Capacity Anodes for Lithium Ion Batteries”, 219th ECS meeting at Montreal, Canada – Oral Presentation
  - R. Epur, M. K. Datta, W. Wang, J. Maranchi, P. Jampani and P. N. Kumta, “Silicon/ Carbon based nanocomposite anodes for lithium-ion batteries”, 218th ECS meeting at Las Vegas, NV, USA - Oral presentation
  - R. Epur, W. Wang, M. K. Datta and P. N. Kumta, “Hybrid nanostructures of silicon and vertically aligned multiwalled carbon nanotubes: Reversible high capacity lithium ion anodes”, 218th ECS meeting, Las Vegas, NV, USA – Poster
  - R. Epur, W. Wang and P. N. Kumta “Carbon nanotube and silicon based novel heterostructures as high capacity anodes for lithium ion batteries”, 15th IMLB meeting 2010, Montreal, Canada – Poster
  - R. Epur, W. Wang and P. N. Kumta, “ Nanostructured hybrid silicon/Carbon nanotube hetereostructures: Novel reversible high-capacity lithium-ion anodes”, 217th ECS meeting 2009, Vancouver, Canada – Oral presentation
  - P.N. Kumta, “Nano-scale Engineered Electrochemically Active Silicon Based Heterostructures” MRS meeting, Boston (2011) – Oral presentation
- **Patent**
  - P.N. Kumta, “Nano-Scale Silicon Based Compositions and Methods of Preparation”, Patent Filed, September 2010.

TECHNICAL BACK – UP SLIDES

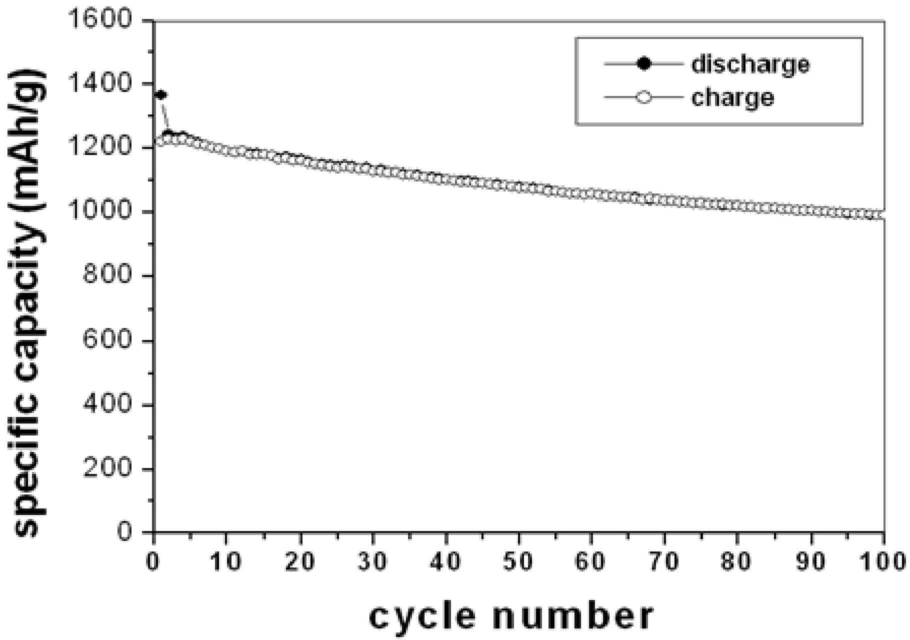
1st cycle irreversible loss of Nanoparticle Si used in the present study

Nanoparticle Si (MTI Corporation): spherical crystalline
Particle size: 100nm, surface area: 80m^2/g,



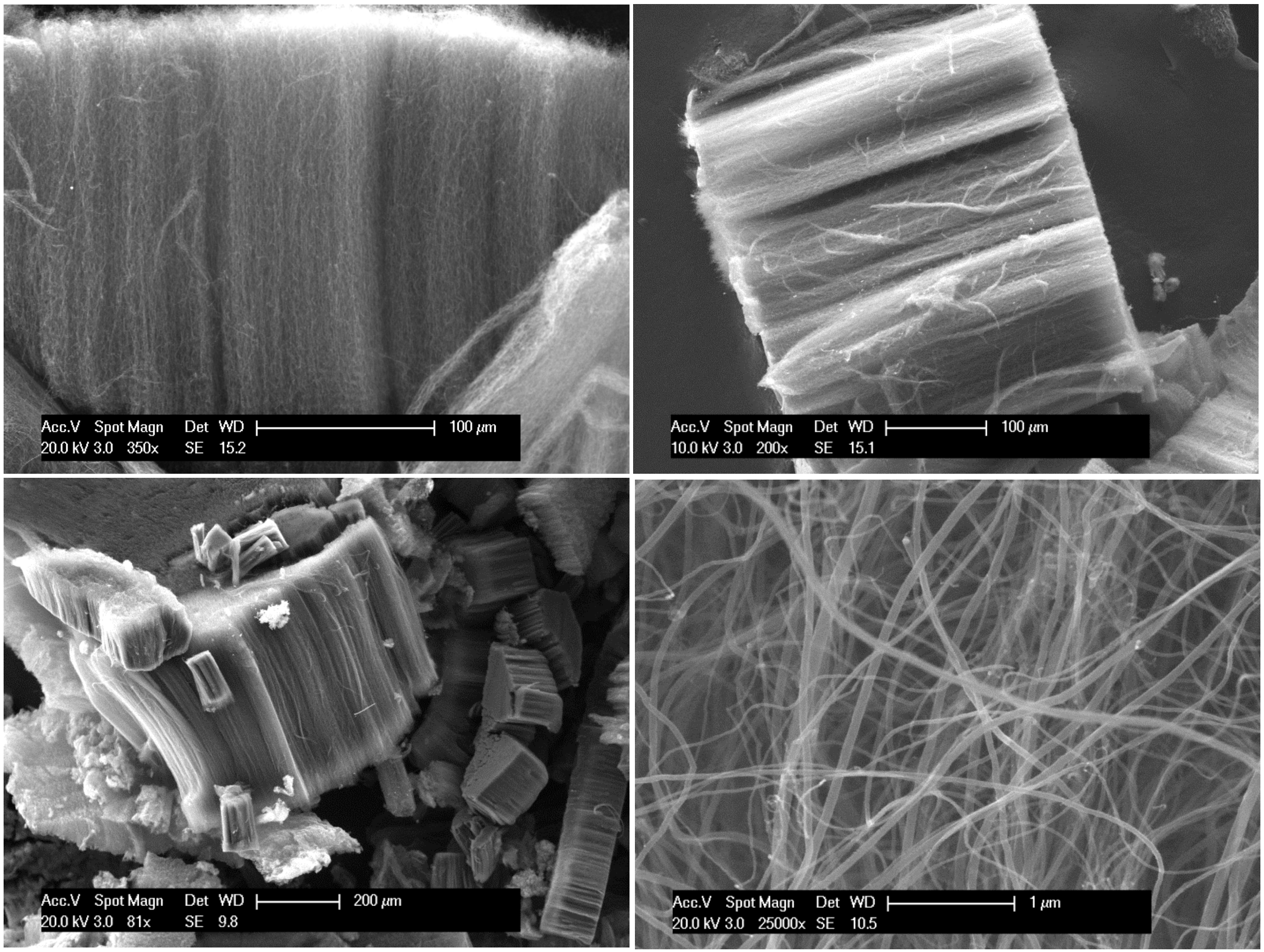
Cycled at 160mA/g, 0.02V-1.2V
1st cycle discharge capacity ~1500mAh/g
and 1st cycle charge capacity ~1260mAh/g
with an irreversible loss of only ~16%

Long cycle life of nc-Si/KS6 composite

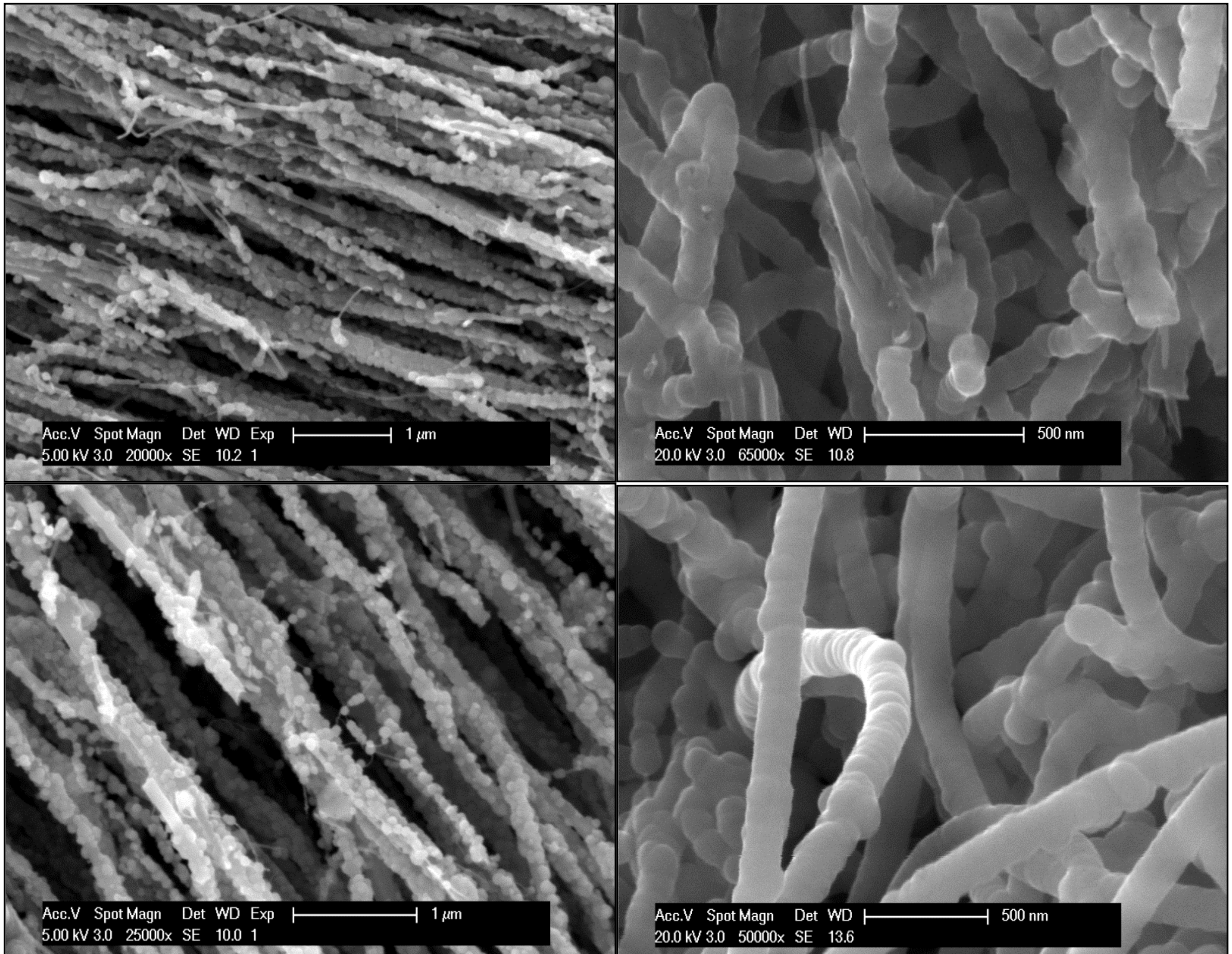


Cycled at 160mA/g, 0.02V-1.2V
1st cycle discharge capacity ~1400mAh/g and 1st cycle charge capacity ~1200mAh/g with an irreversible loss of only ~10%.
Fade in capacity: 0.19% per cycle upto 100 cycles

Vertically aligned CNTs by CVD

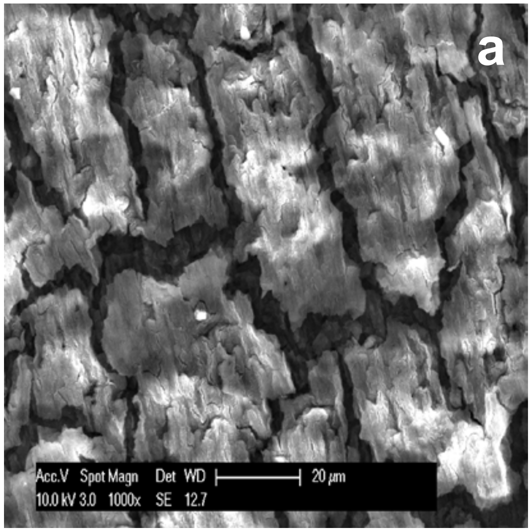


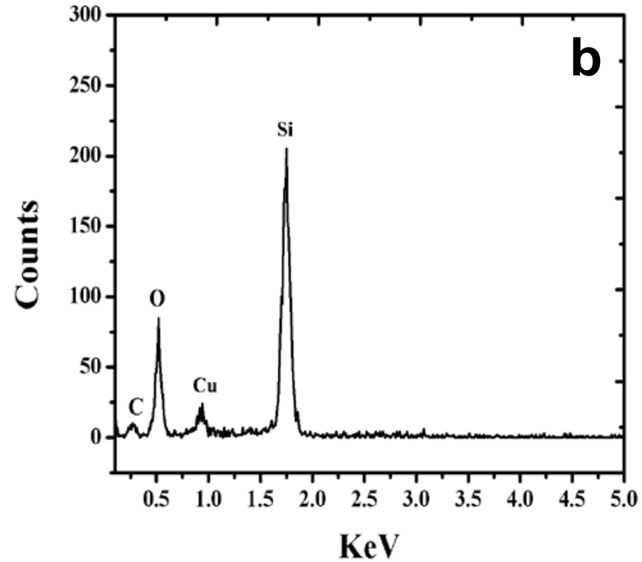
CNT/Si Heterostructures by CVD

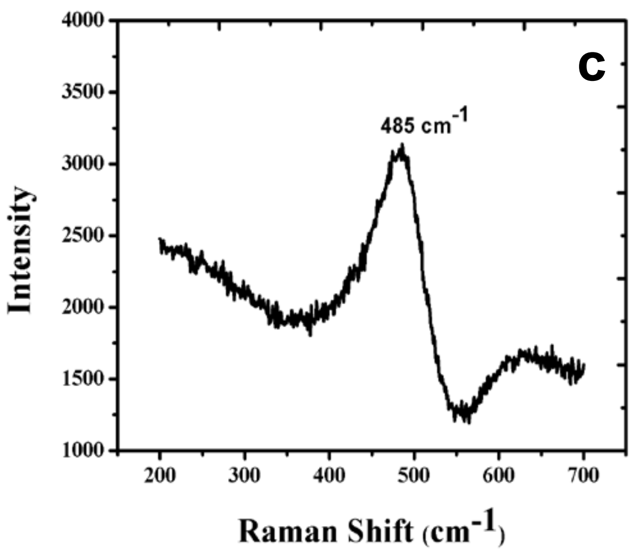


Other low cost approaches for generating large area amorphous silicon

SEM/EDAX/Raman of *a*-Si derived by electrochemical reduction







(a) SEM (b) EDAX & (c) Raman results of the electrodeposited *a*-Si film on copper foil

Electrochemical characterization of *a*-Si films derived by electrochemical reduction