NATIONAL ENERGY TECHNOLOGY LABORATORY

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New High Energy Density Mg Battery Concepts for Electrical Energy Storage

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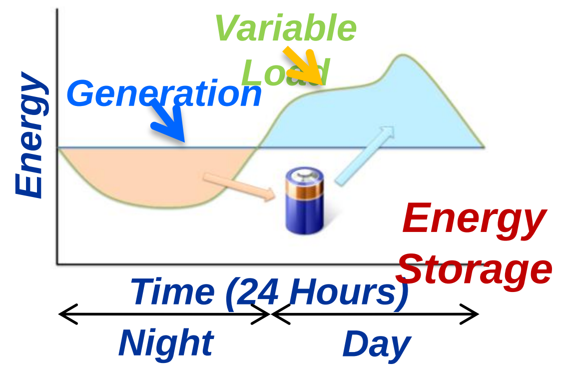
Outline

- **Introduction**
- **Objectives**
- **Approaches**
  - Anodes
  - Cathodes
  - current collectors
  - electrolytes
- **Results**
- **Summary**
- **Future work**

Electrical Energy Storage and the Smart Grid

Electrical Energy Storage
A key enabler for the smart grid

www.netl.doe.gov/smartgrid



Advantages of the smart grid:

- Improve reliability and stability of the grid
- Provide responsive power to meet minute-to-minute fluctuations in electricity demand and increase margins against system upsets
- Provide capacity to “peak shave or load shift,” enabling peak loads to be met during periods when generation, transmission and distribution assets can not yet be brought on line
- Improve efficiency of off-grid solar and wind power enabling the integration onto the grid of large scale renewable energy plants
- More stable and efficient delivery of electrical power <u>– including power generated from fossil fuel sources</u>

Electrical Energy Storage - result in more stable and efficient delivery of electrical power while reducing overall CO_2 emissions

Performance Targets and Needs for Electrochemical Energy Storage for Grid Applications*

Five year targets:

- System capital cost: under \$250/kWh
- Levelized cost: under 20 ¢/kWh/cycle
- System efficiency: over 75%
- Cycle life: more than 4,000 cycles

Long term targets:

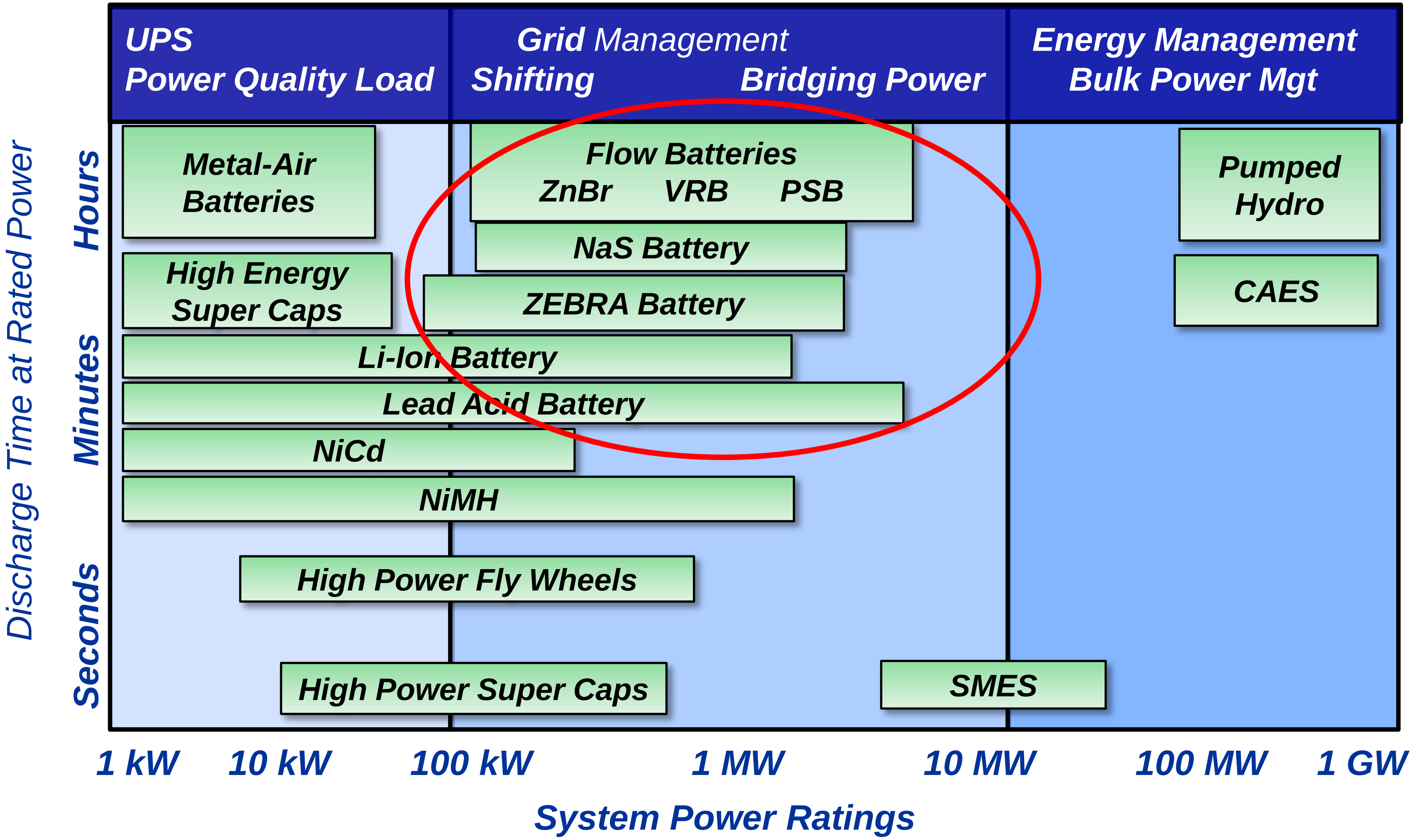
- System capital cost: under \$150/kWh
- Levelized cost: under 10 ¢/kWh/cycle
- System efficiency: over 80%
- Cycle life: more than 5,000 cycles

NEEDS :

- *Optimize materials and chemistries and modify current technologies to improve their performance and reduce costs.*
- *Discover new materials and components that can lead to new technologies meeting the performance and cost requirements of grid storage applications.*

** Source: US DOE Office of Electricity Delivery & Energy Reliability (OE), Energy Storage Planning Document, February, 2011*

Current Grid Scale Batteries



Source: Figure adapted from EPRI report, "Integrated Distributed Generation and Energy Storage Concepts," (2003) Product ID 1004455.

State of the Art in Battery Technologies

Battery type	**Cell voltage (V)**	**Energy per kg (Wh/kg)**	**Specific power (W/kg)**	**Direct use**	**Technical and cost barriers**
Lead acid	2.1	30-40	180	Automotive engine ignition	Moderately expensive; Moderate energy density; Environmental hazard due to Lead.
Ni-Cd	1.2	40-60	150	wireless telephones, emergency lighting, aircraft starting & standby power	Inexpensive, Moderate energy density; memory effect; Environmental hazard due to Cadmium.
Ni-MH	1.2	30-80	250-1000	Portable electronic device, flashlights	High self-discharge rate
Lithium ion	3.6	180	250-340	Laptop computers, mobile devices, some modern automotive engines,	Reduced first-cycle capacity loss and volumetric expansion of intermetallic electrodes
Lithium -air	3	13,000		Portable electronic devices, electric vehicles	Poor cycle life times; Potential for formation of shorting dendrites when charged
Na-S	2.1	110	150	Electricity storage for grid support	High temp 350 C
Zebra	2.6	100	150	Electric vehicles, energy storage for grid	High temp 270 ˚C

Current Battery Technologies for Grid Storage:
Mg a possible solution to the grid-lock

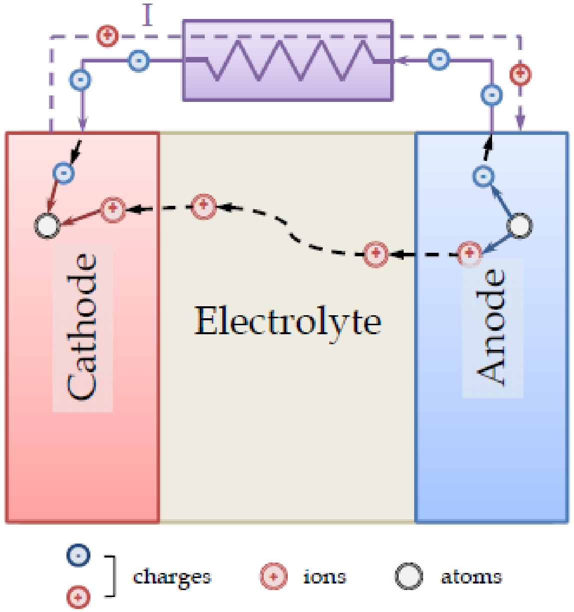
BATTERY	ZEBRA	NaS	Mg
Anode	Molten metallic Na	Molten Metallic Na	Solid Mg alloy
Cathode	$NiCl_2$ or $NaAlCl_4$	Molten S or Na_2S_x	$Mg_{1.03}Mn_{0.97}SiO_4$
Electrolyte	β''-Al_2O_3 solid electrolyte (BASE)	β''-Al_2O_3 solid electrolyte (BASE) membrane	$Mg(AlCl_2BuEt)_2$/THF (0.25 mol L^{-1})
Cell Voltage	2.58 V	2.1 V	2.1 V
Specific Capacity*	305 Ah/kg	377 Ah/kg	315 Ah/kg**
Specific Energy*	100 Wh/kg	110 Wh/kg	~500 Wh/kg
Operating Temperature	***High 270°C***	***High 350°C***	***Room Temp***

**Theoretical*
***based on cathode*

Mg based Batteries for Grid Scale Electrical Energy Storage

Why Magnesium?

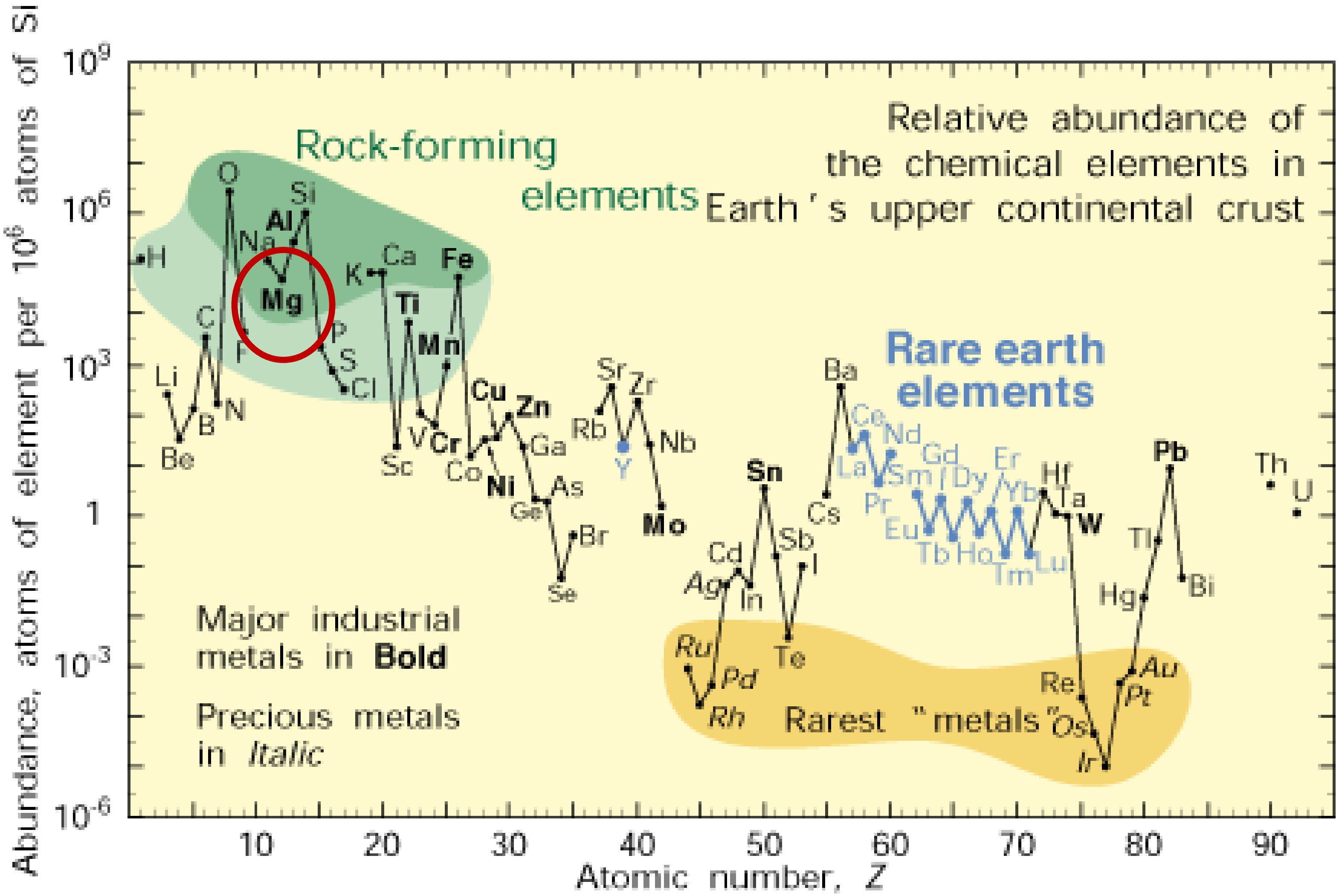
- **Mg batteries involve cycling Mg^{2+}**
  - Provides 2 electrons. Theoretical specific capacity: 2205 Ah/kg
- **Mg compounds are environmental stable "green" and non-toxic. Mg alloys can be readily stabilized.**
- **Mg as a raw materials is cheap and abundant**
  - Mg: ~ $2700/ton
  - Li: ~ $64,000/ton
  - Mg: ~ 13.9% earth's crust
  - Li: ~ 0.0007% earth's crust



Systems with Proper Designs and Architectures:

- ***200-1000 Wh/kg***
- ***1-3 V***

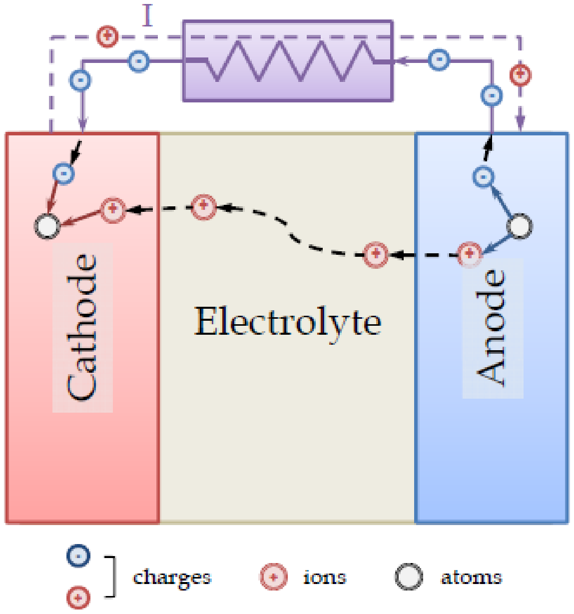
Mg Abundance in Earth's Crust



Mg based Batteries for Grid Scale Electrical Energy Storage

Key Challenges

- **Electrolytes**
  - Solvents: neither donate or accept protons
  - Solvents: Not allow the formation of passivating surface films onto Mg anode
- **Cathodes**
  - Difficulty in intercalation of Mg ions
  - Cycling of Mg systems is quite poor
  - Cycling is a key requirement for a rechargeable battery



Rechargeable Mg batteries recent work:

- **Electrolytes**
  - *Aurbach et al* [1,2]*: Magnesium-organohaloaluminate salts*
- **Cathodes**
  - *Aurbach et al* [1,2] *:* $MgMo_3S_4$
  - *NuLi et al* [3]*:* $Mg_{1.03}Mn_{0.97}SiO_4$
- **Anodes**
  - *Aurbach et al* [1,2] *: Mg foil, AZ31*

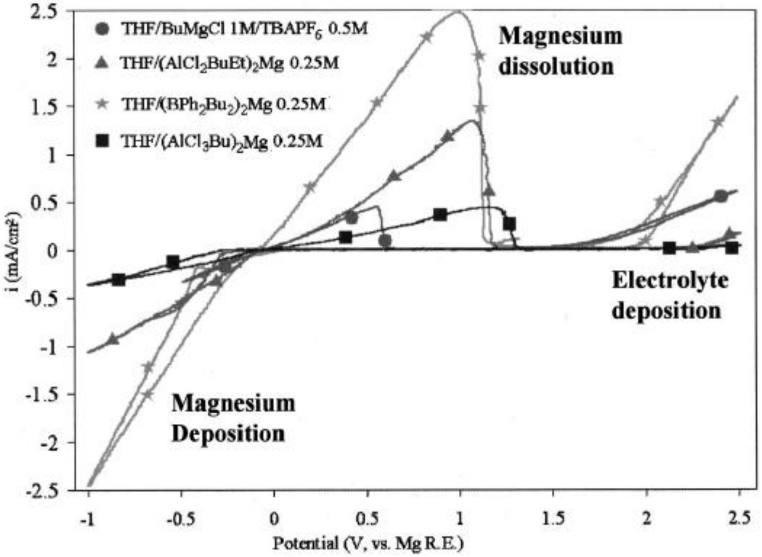
1) *D. Aurbach et al, Advanced Materials, 2007, v19, p 4260*
2) *E. Levi et al, Chem. Materials, 2010., v22, p. 860*
3) *Y. NuLi et al. Chem. Comm. 2010, v46., p. 3794.*

Research Objectives

- **Explore new current collectors concepts**
  - Anodic stability and electrochemical window (key)
  - Opportunities for cost effective concepts
- **Explore new cathode concepts**
  - New intercalation concepts (key)
  - Novel inorganic compounds
  - New insertion and Redox chemistries (key)
- **Explore new anodic concepts for Mg**
  - Novel alloy design concepts for Mg anodes (key)
  - Explore corrosion resistant alloy designs
- **Explore new electrolyte concepts for Mg batteries**
  - Identify new non-aqueous liquid electrolytes (key)
  - Explore ionic liquids as potential electrolytes

Prior art in Mg Rechargeable batteries

Electrolyte shows high Mg cycling efficiency (~95%) & electrochemical stability window (~2.1 V)



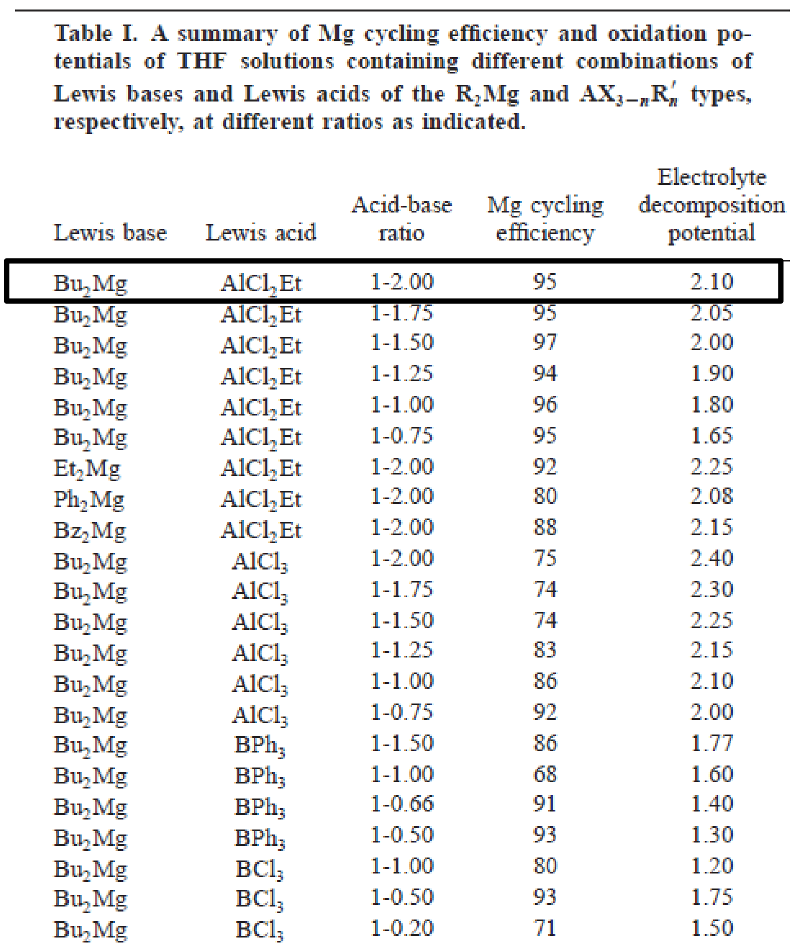


Table I. A summary of Mg cycling efficiency and oxidation potentials of THF solutions containing different combinations of Lewis bases and Lewis acids of the R_2Mg and $AX_{3-n}R'_n$ types, respectively, at different ratios as indicated.

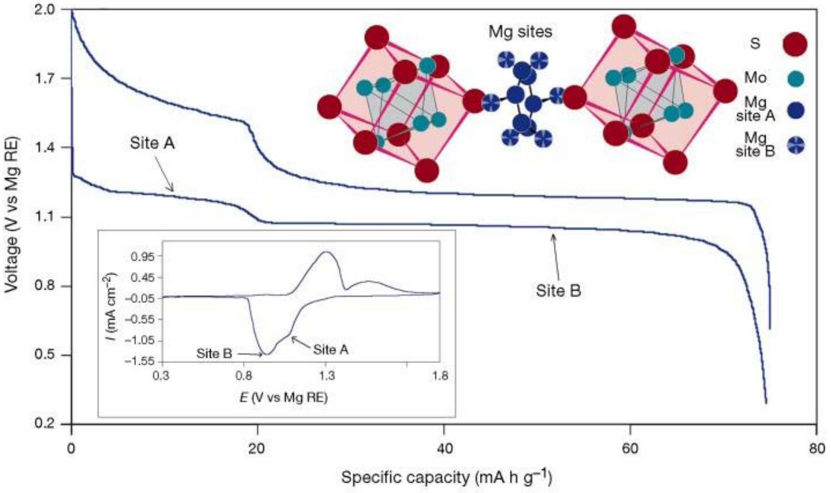
Lewis base	Lewis acid	Acid-base ratio	Mg cycling efficiency	Electrolyte decomposition potential
Bu_2Mg	$AlCl_2Et$	1-2.00	95	2.10
Bu_2Mg	$AlCl_2Et$	1-1.75	95	2.05
Bu_2Mg	$AlCl_2Et$	1-1.50	97	2.00
Bu_2Mg	$AlCl_2Et$	1-1.25	94	1.90
Bu_2Mg	$AlCl_2Et$	1-1.00	96	1.80
Bu_2Mg	$AlCl_2Et$	1-0.75	95	1.65
Et_2Mg	$AlCl_2Et$	1-2.00	92	2.25
Ph_2Mg	$AlCl_2Et$	1-2.00	80	2.08
Bz_2Mg	$AlCl_2Et$	1-2.00	88	2.15
Bu_2Mg	$AlCl_3$	1-2.00	75	2.40
Bu_2Mg	$AlCl_3$	1-1.75	74	2.30
Bu_2Mg	$AlCl_3$	1-1.50	74	2.25
Bu_2Mg	$AlCl_3$	1-1.25	83	2.15
Bu_2Mg	$AlCl_3$	1-1.00	86	2.10
Bu_2Mg	$AlCl_3$	1-0.75	92	2.00
Bu_2Mg	BPh_3	1-1.50	86	1.77
Bu_2Mg	BPh_3	1-1.00	68	1.60
Bu_2Mg	BPh_3	1-0.66	91	1.40
Bu_2Mg	BPh_3	1-0.50	93	1.30
Bu_2Mg	BCl_3	1-1.00	80	1.20
Bu_2Mg	BCl_3	1-0.50	93	1.75
Bu_2Mg	BCl_3	1-0.20	71	1.50

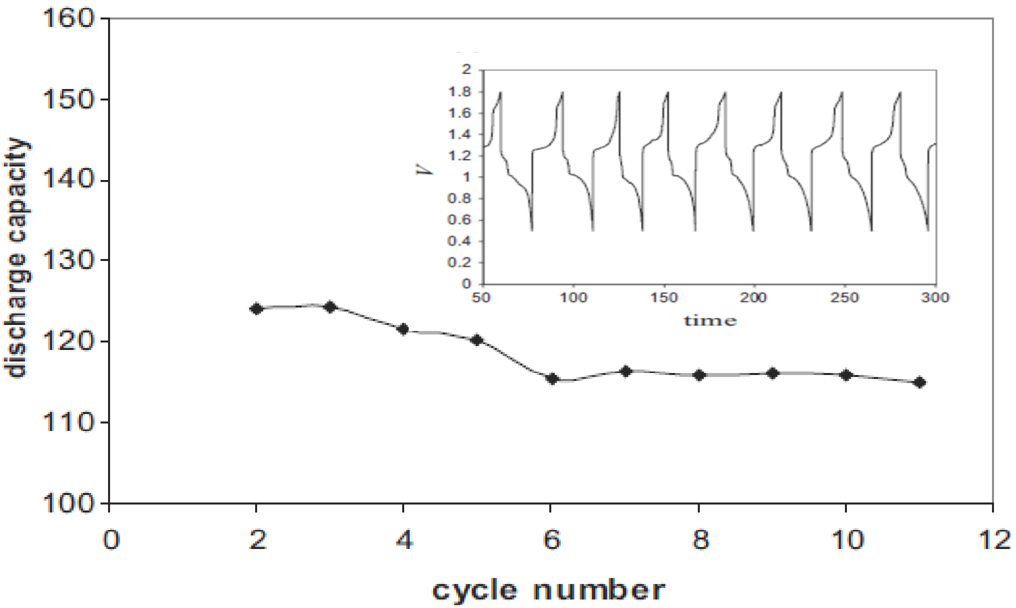
CV performed using platinum WE, magnesium foil CE and RE with the electrolyte shows reversible Mg/Mg^{2+} deposition/dissolution occurs (within the electrochemical potential window of ~ 2.1 V with excellent Mg cycling efficiency

Aurbach *et al. J. Electrochem Soc.*, 149 (2), (2002), A115-21

New Intercalation cathode: $Mg_xMo_3S_4$ (0<x<1)

Chevrel phase cathode (Mo_6S_8) in $Mg(AlCl_2BuEt)_2$/THF (0.25 mol L^{-1}) electrolyte solution where reversible intercalation of Mg^{2+} occur





Maximum charge capacity 122 $mAhg^{-1}$ > 1000 cycles

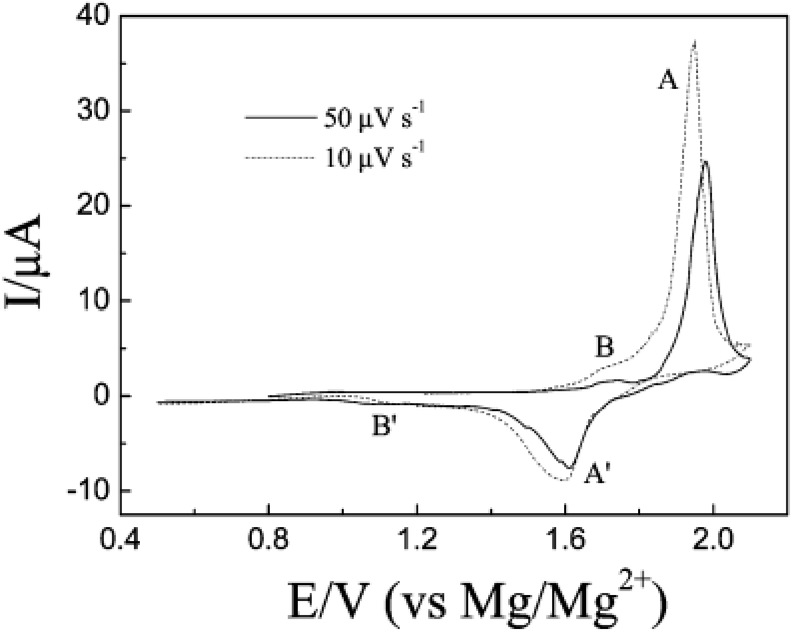
Practical energy density ~ 60 $Whkg^{-1}$

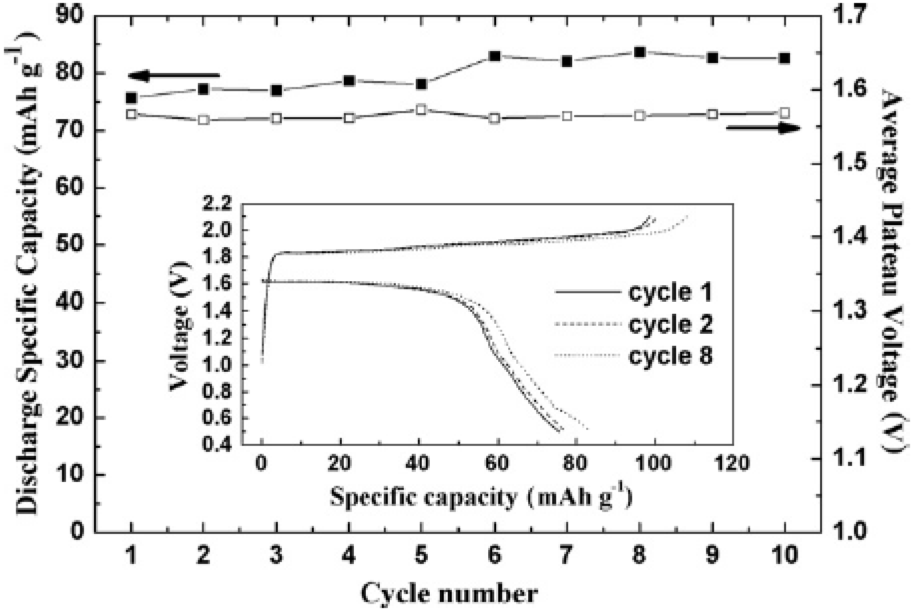
Aurbach *et al*. *Nature*, 407 (10), (2000), 724-27

Chusid *et al*. *Adv. Mater*., 15, (2003), 627-30

Mesoporous $Mg_{1.03}Mn_{0.97}SiO_4$ cathode

Mesoporous $Mg_{1.03}Mn_{0.97}SiO_4$ synthesized by sol-gel route shows reversible intercalation of Mg^{2+} using $Mg(AlCl_2BuEt)_2$/THF (0.25 mol L^{-1}) electrolyte



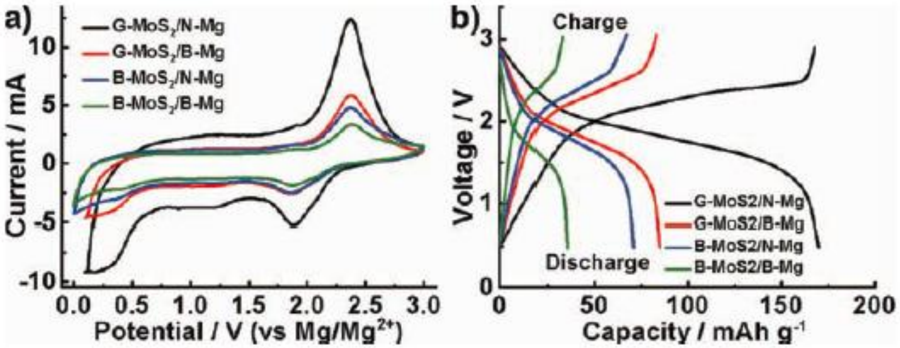


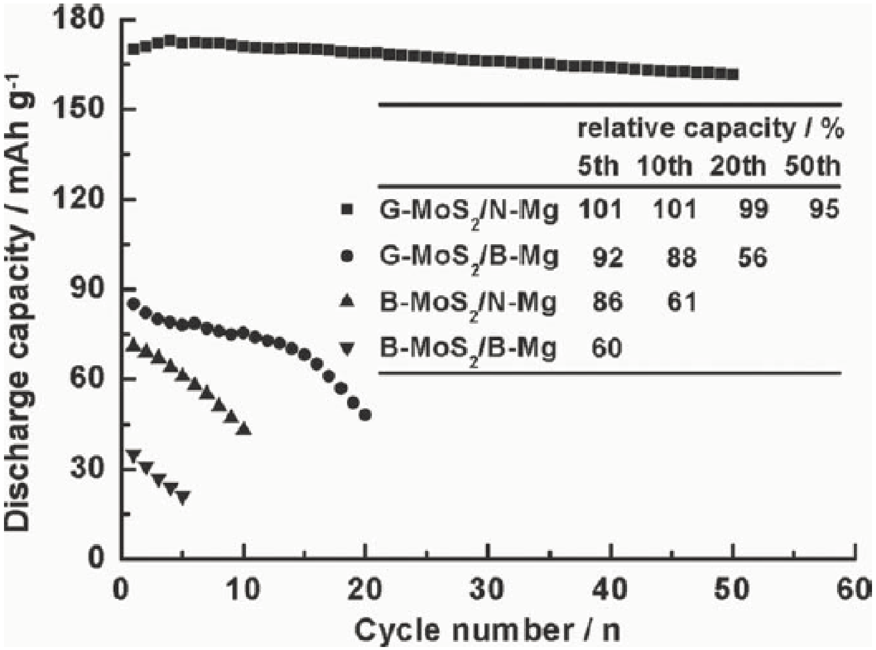
The reversible capacity ~ 80 $mAhg^{-1}$ up to 80 cycles

Nuli *et al. J.Phys. Chem.C., 113, (2009), 594-97*

Feng *et al. J. Power 184, (2008), 604-09*

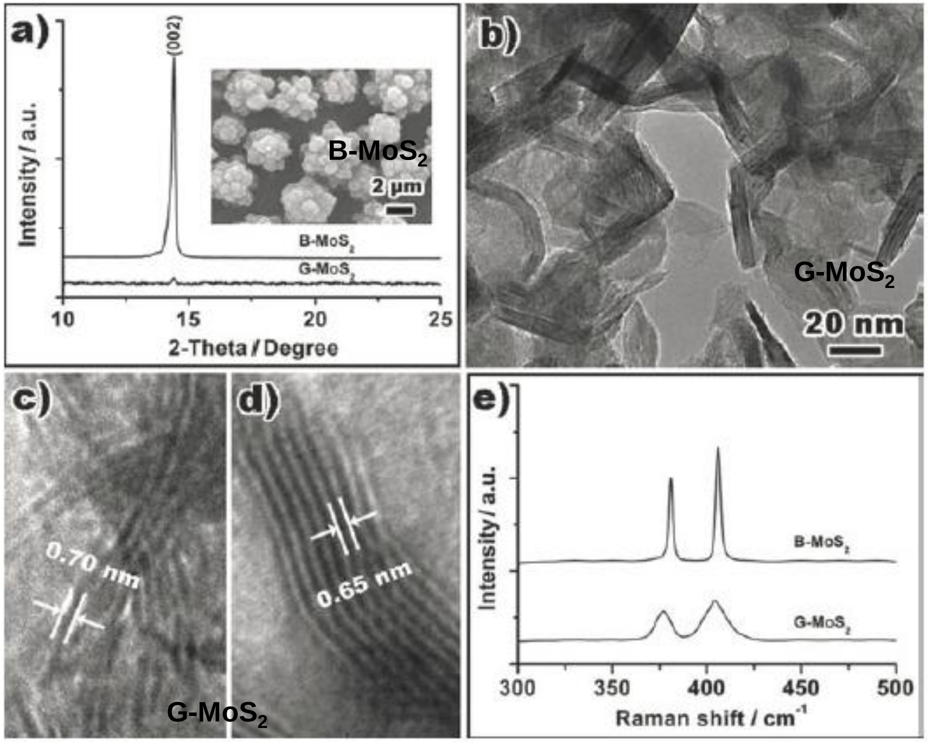
Graphene like MoS_2 cathode and nano-Mg anode shows improved reversible capacity





	relative capacity / %			
	5th	10th	20th	50th
■ G-MoS$_2$/N-Mg	101	101	99	95
● G-MoS$_2$/B-Mg	92	88	56	
▲ B-MoS$_2$/N-Mg	86	61		
▼ B-MoS$_2$/B-Mg	60			

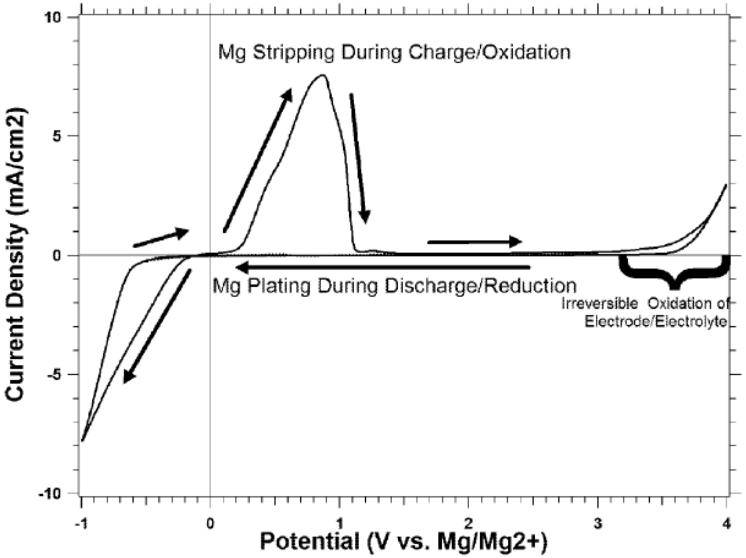
The combination of G-MoS_2 cathode and N-Mg anode has achieved operating voltage of 1.8 V and a 1st discharge capacity of 170 mAhg^{-1} (95% is kept after 50 discharge − charge cycles) in $Mg(AlCl_3Bu)_2$ electrolyte



Liang *et al. Adv. Mater., 23, (2011), 640-43*

Current collector is a key factor for the anodic stability of the electrolytes

Anodic stability of the current collectors is a critical factor for the stability of the electrolyte and stable electrochemical window



Pellion Technologies

PhMgCl : $AlCl_3$ = 2:1 (~ 3 V electrolyte developed by Aurbach *et al*.)

Current Collector Candidate	Anodic Stability Limit (I > 100uA/cm^2)
Pt	2.90
Au	2.61
Ni	2.01
Ti	2.58
Glassy Carbon	**2.85**
Carbon Sheet (Graphfoil and Fiber)	**2.99**

Carbon sheet shows the highest stability ~ 3 V

Need for improvement

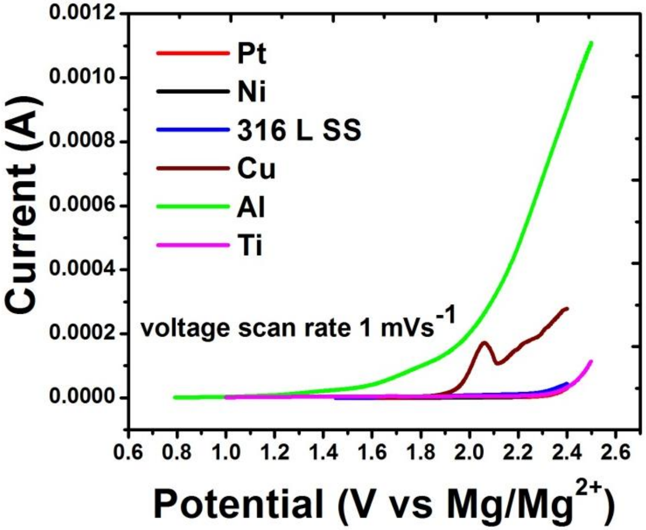
R. E. Doe, G. E. Blomgren, and K. A. Persson, "RECHARGEABLE MAGNESIUM ION CELL COMPONENTS AND ASSEMBLY," United States Patent, 2011

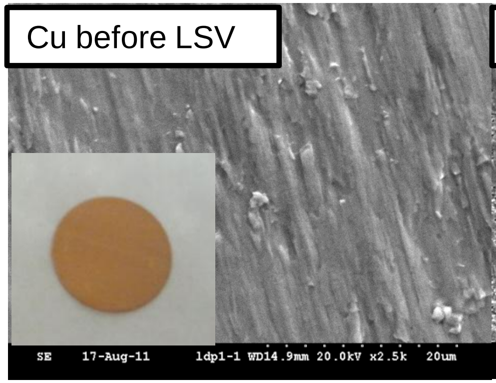
Results and Accomplishments

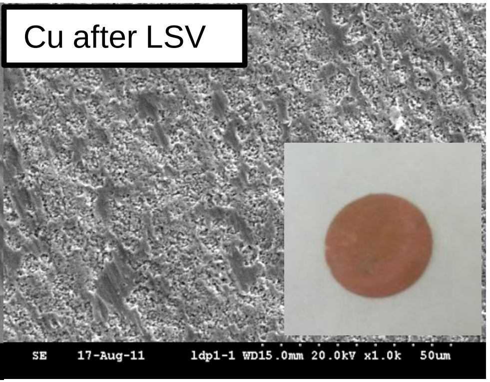
Analysis of current collectors

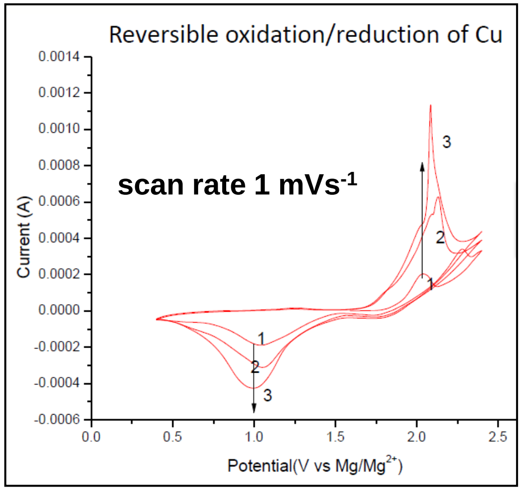
Current collectors in Mg(AlCl$_2$EtBu)$_2$/0.25 M THF electrolyte

LSV on Cu,Ni, Al, Ti, 316 L SS and Pt.







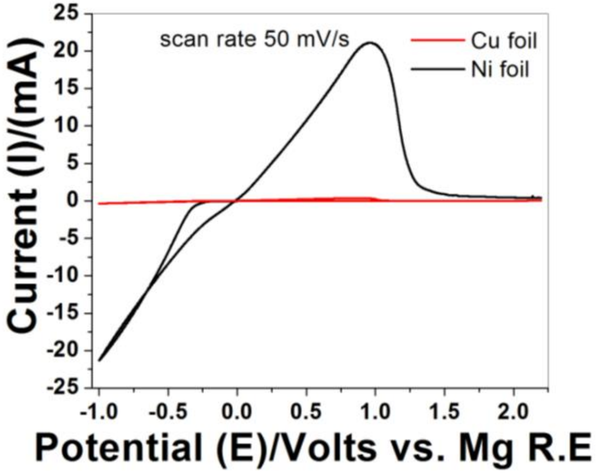


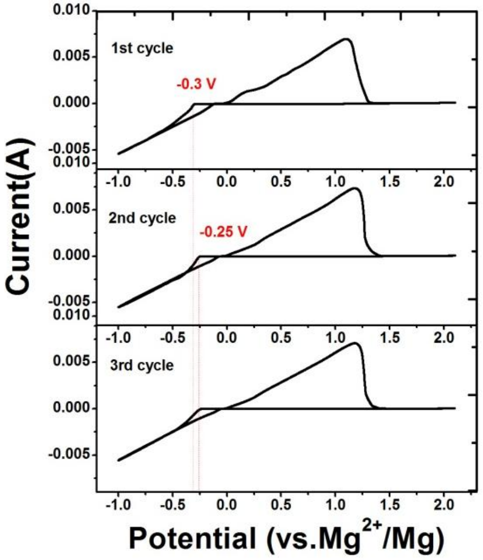
Anodic stability of the current collectors (Cu, Ni, Al, Ti, 316L SS, and Pt) was tested in Mg(AlCl$_2$EtBu)$_2$/THF electrolyte

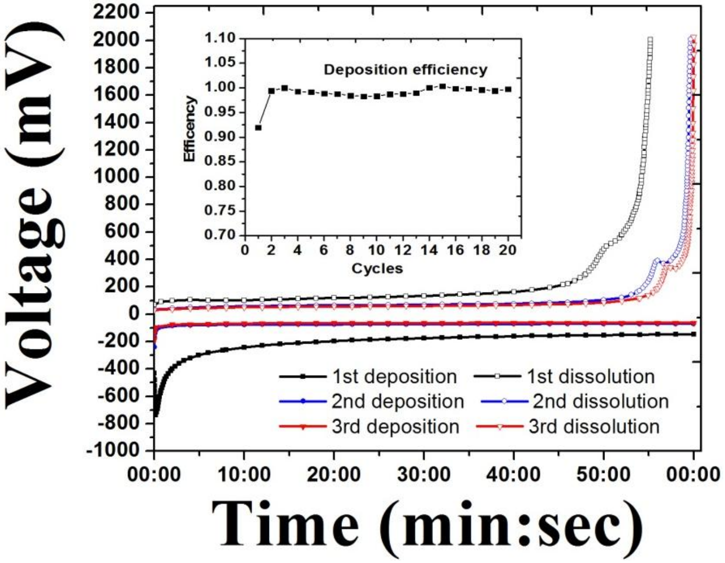
Al, Cu and 316L SS are not stable enough in the present electrolyte

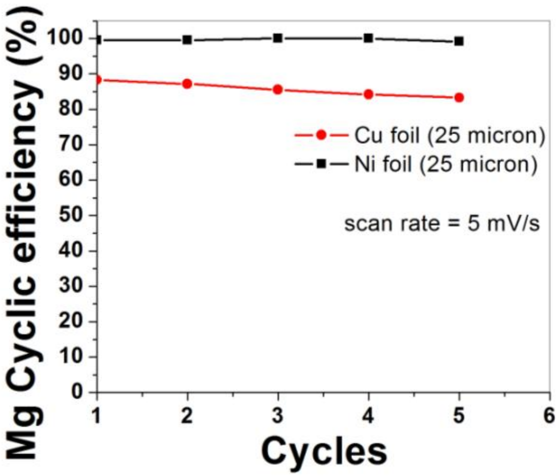
Commonly used current carriers do not work for Mg!!

Current collectors in Mg$(AlCl_2EtBu)_2$/0.25 M THF electrolyte



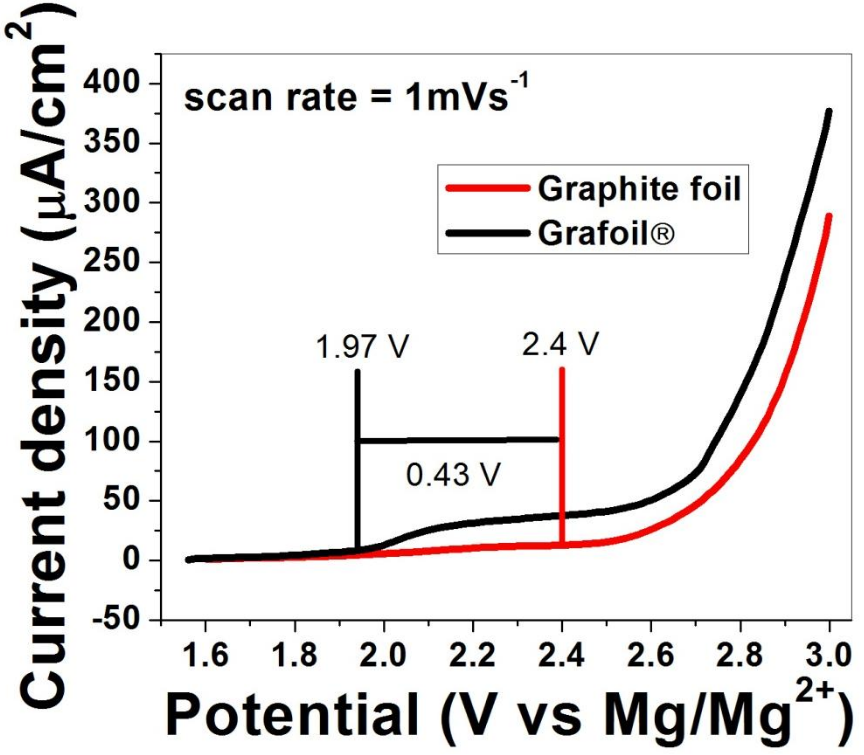






Ni is a good choice as current collector with excellent stability and high deposition/dissolution efficiency

Carbon based Current collectors in $Mg(AlCl_2EtBu)_2$/0.25 M THF electrolyte



Anodic stability of graphite foil is 0.43 V higher when compared to Grafoil®

Graphite foil is an ideal candidate for current collector

Cycles	Scan between OCP to 3 V	Anodic stability limit ($I > 10\ \mu Acm^{-2}$)
Graphite foil	+ ive scan	2.4
Grafoil®	+ ive scan	1.97

Development of new cathodes

Hydrothermal assisted sol-gel synthesis of $MgMnSiO_4$

Mn acetate
Mg acetate
TEOS
Acetic acid

Dispersed in ethanol

Mixture

Hydrothemally treated at 150 ˚C

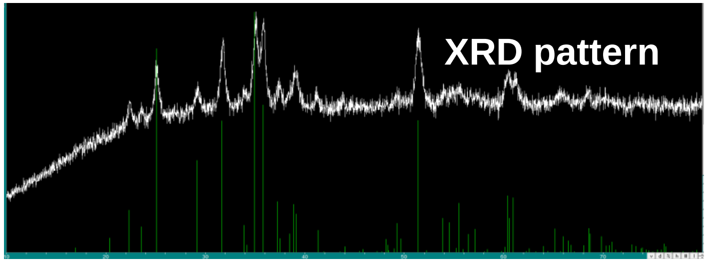
Sol-gel precursor

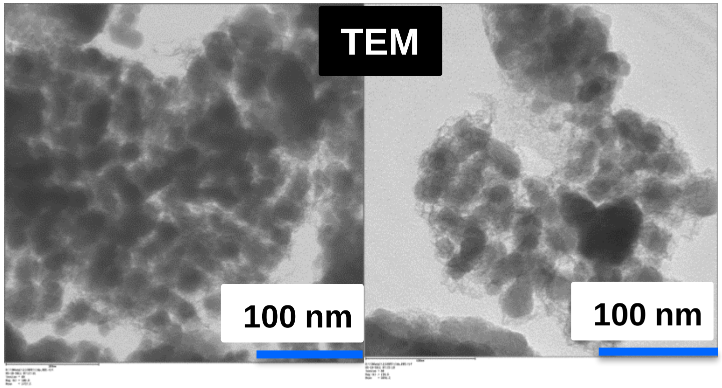
Ball mill with sucrose

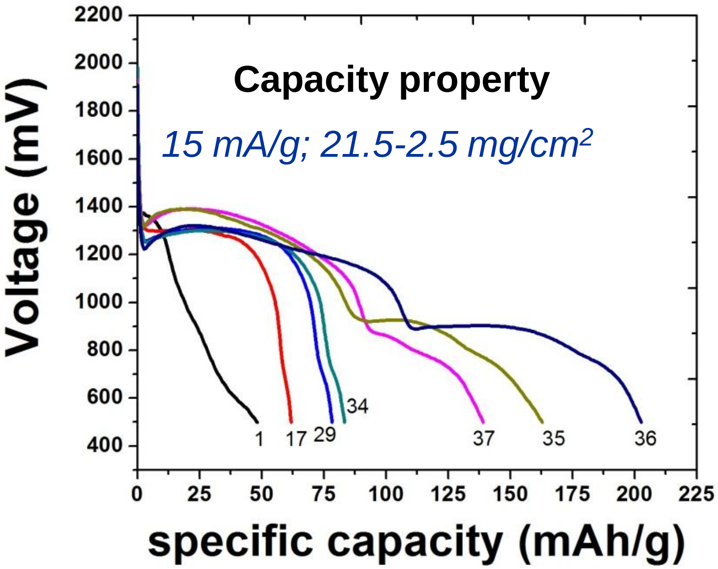
precursor

800 ˚C, Ar

Carbon coated product







Nanosized carbon coated $MgMnSiO_4$ particles was synthesized, characterized and electrochemically tested

MoS_2/Graphene composite

$(NH_4)_2MoO_4$
L-cysteine
Graphene oxide

Dispersed in water →

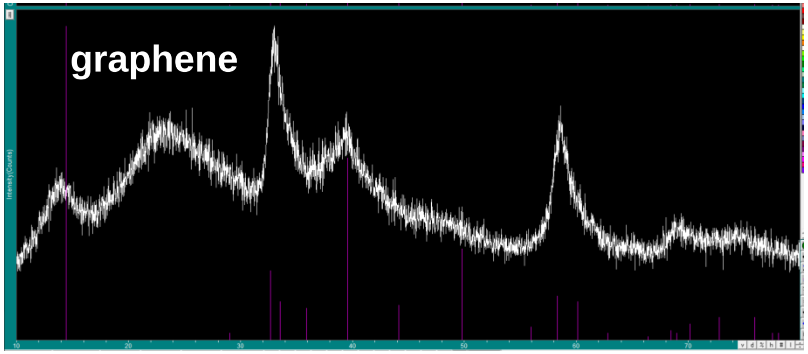
Mixture

Hydrothermal at 200 ˚C →

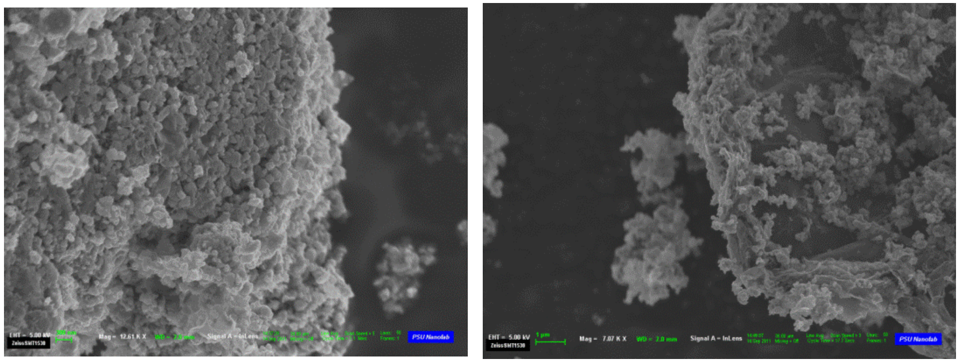
Black precipitation

800 ˚C, H_2/Ar →

product



XRD pattern



SEM images

Nanosized MoS_2/G composite was synthesized, characterized and electrochemically tested

Synthesis and Galvanostatic cycling of Mg compound

Synthesized by Pechini's Route,

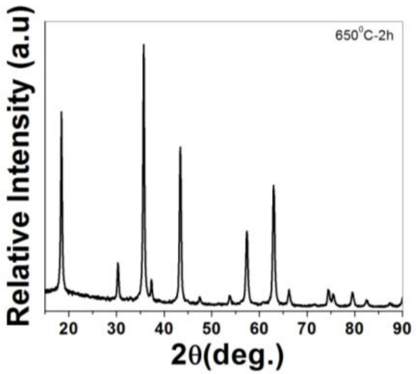
TEM shows ~ 50 nm particles

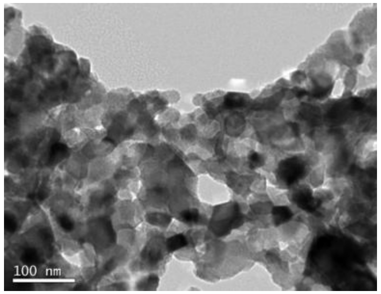
Mg^{2+} intercalation occur at two different voltages ~ 1.7 V and 1.2 V (cyclic voltammogram)

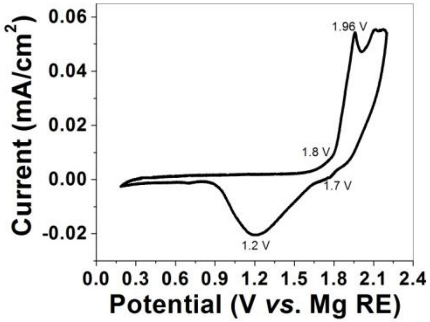
Maximum charge and discharge capacity at 2C rate ~ 18 $mAhg^{-1}$ and ~ 15 $mAhg^{-1}$ respectively

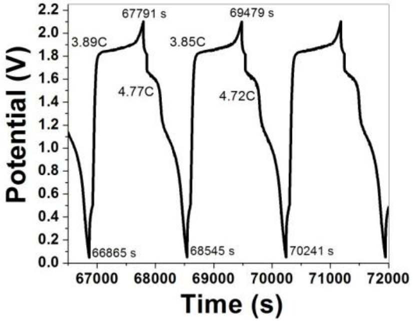
Sp. Capacity increases with Increasing cycle number

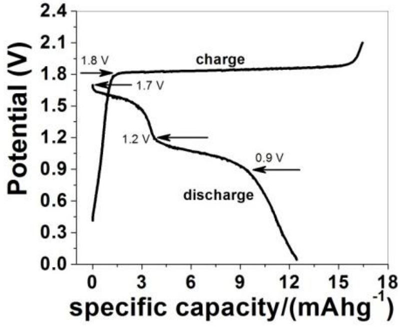
Structural refinement needed

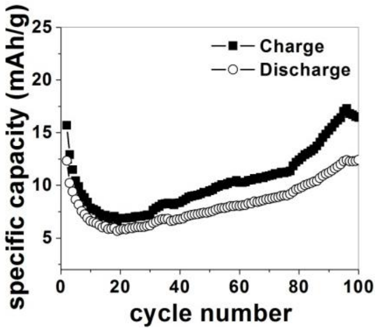




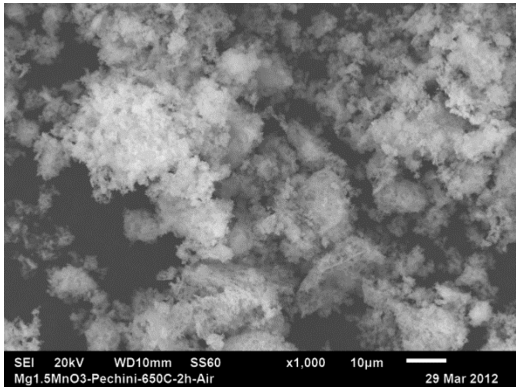


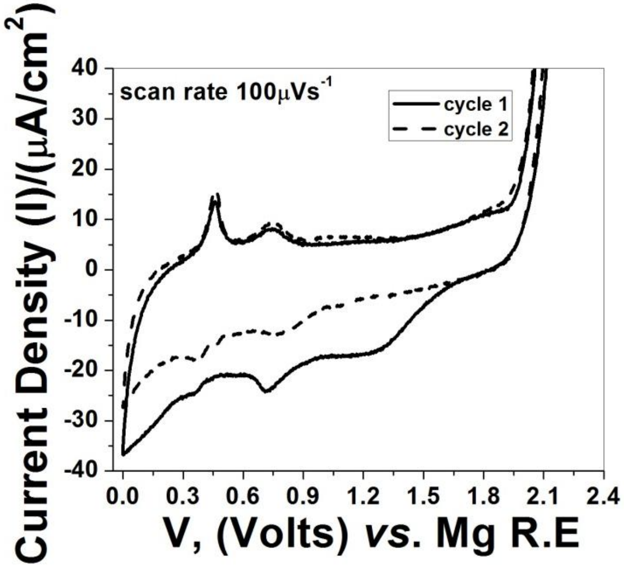


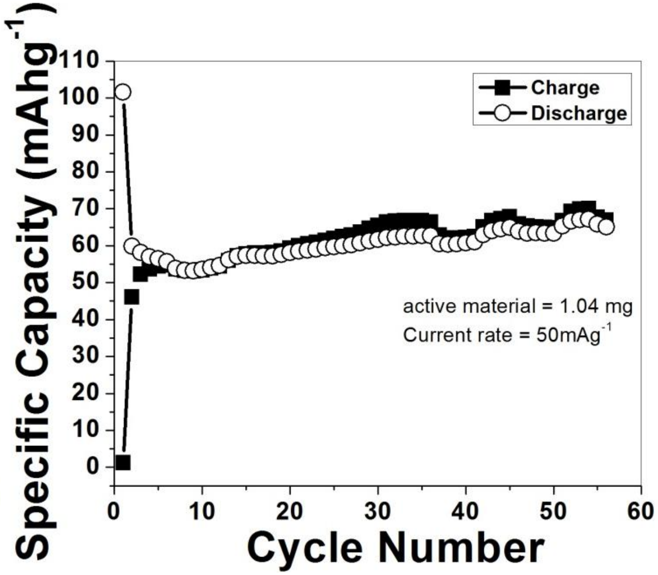




Galvanostatic cyclic data of Mg compound







Raw powder prepared by Pechini's route and heated at 650 ^{0}C for 2 h

SEM shows the uniform sub-micron size spherical particles

Redox peaks: cathodic ~0.45 V and 0.75 V and
anodic ~ 0.71 V and ~ 0.37 V

Max. charge & discharge capacity ~ 70 mAg^{-1} and 67 mAhg^{-1} (C/2 rate)

Development of new anodes

Theoretical sp. capacity of a new Mg compound is 26% more than pure Mg

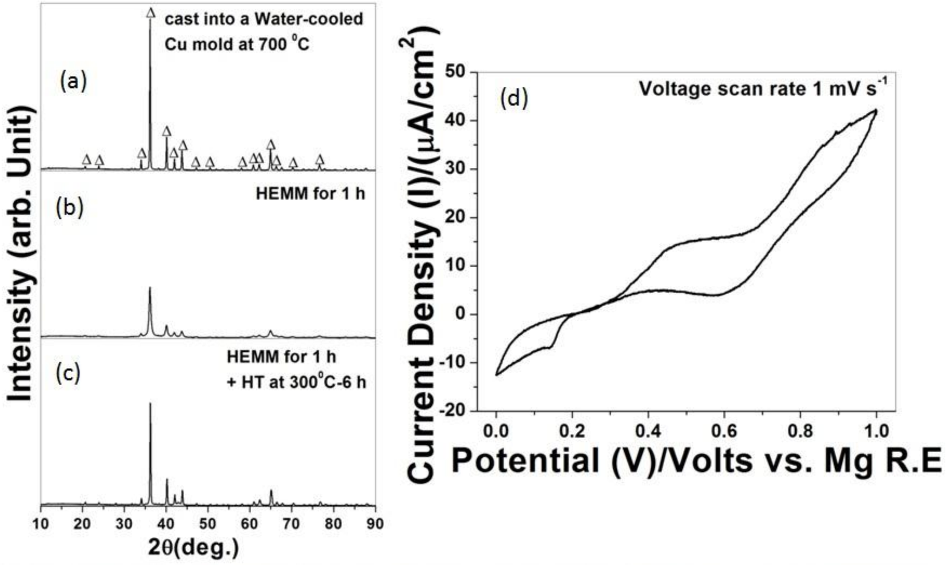
Rapid Solidification Processing (RSP)

Stoichiometric amount of elemental shots melted in a steel crucible at 700 ˚C and cast into water-cooled Cu mold

Powder XRD-patterns confirm the formation of desired phase

Sample subjected to ball milling for a duration of 1 h

Ball-milled powder characterized by XRD to confirm presence of desired phase. Final powder was heated at 300º C -6 h and thereafter used for electrode preparations



Cyclic voltammogram shows material is active

During charging Mg leaves the parent structure (Mg de-alloying occurs ~ 0.45 V), further Mg de-alloying occur at ~ 0.85 V)

During discharge cycle Mg^{2+} alloying occurs at ~0.6 V and at ~ 0.12 V

Plans in place to form thin films (~ 50 nm) to test the intrinsic cycling capacity

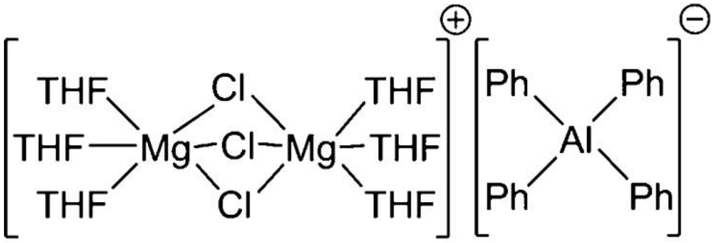
	Theoretical Specific Capacity	Percent Improvement
Pure Mg	2233 Ah kg^{-1}	**26%**
Mg compound	2819 Ah kg^{-1}	

Development and analysis of novel non-aqueous electrolytes

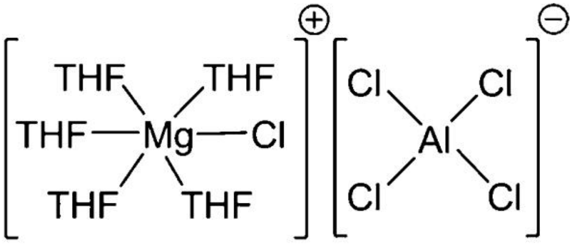
Goals: Development of Electrolytes

- Identify and develop novel non-aqueous organic liquid as well as ionic liquid based electrolytes with potential window (~ 4 V) than state of the art electrolyte (maximum potential window ~ 3 V)
- Use of non-flammable solvents for electrolytes
- Excellent cyclability of Mg dissolution/deposition process
- No side reactions

State of the art in Electrolytes for Mg battery



C4



C2

- ➢ The equilibrium species are results of transmetallation reaction in this system
- ➢ Rapid ligand exchange between the Al and Mg core allows the reversible deposition and dissolution of Mg

Drawbacks

- ➢ THF is highly flammable and difficult to handle (Safety issues)
- ➢ Potential window needs to be increased for next generation of Mg Batteries

Aurbach *et al. J. Am. Chem. Soc.*, 2011, *133* (16), pp 6270–78

Development of Organometal based Non-aqueous Mg Electrolytes

Development of 1st generation $Mg(AlCl_2BuEt)_2$/Tetrahydrofuran (0.25 mol L^{-1}) non-aqueous liquid electrolyte

Bu_2Mg (1 mol L^{-1} in heptane) + $AlCl_2Et$ (1 mol L^{-1} in hexane) mixed in the molar ratio of 1:2 at R.T. (transmetallation)

↓

A white solid precipitate

↓

Stir for 48 h to evaporate the heptane/hexane

↓

White solid, dissolved in anhydrous THF

↓

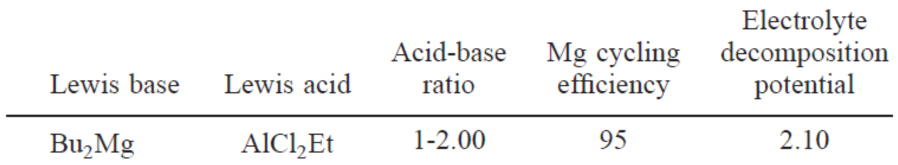
Mg can be electrochemically deposited and dissolved reversibly from this solution

Aurbach *et al. J. Electrochem Soc.*, 149 (2), (2002), A115-21

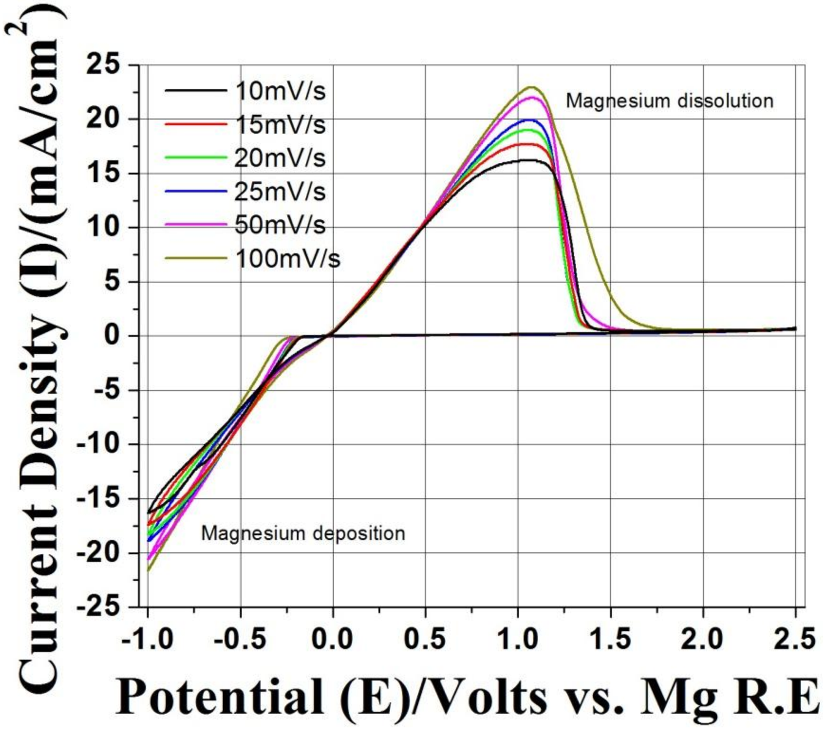
Successfully synthesized $Mg(AlCl_2BuEt)_2$/ (0.25 M THF) based 1st generation non-aqueous electrolyte (potential window ~ 2.1 V)

Mg/Mg^{2+} deposition/dissolution occurs within the electrochemical potential window of ~ 2V indicative of good electrolyte function as expected

Scan rate (mV/s)	Onset deposition potential (V)	Anodic stripping peak potential (V)	Mg cycling efficiency (%)
10	-0.170	1.006	99.3
15	-0.180	1.006	98.3
20	-0.182	1.023	96.3
25	-0.193	1.032	95
50	-0.21	1.06	93.6
100	-0.23	1.051	94.3

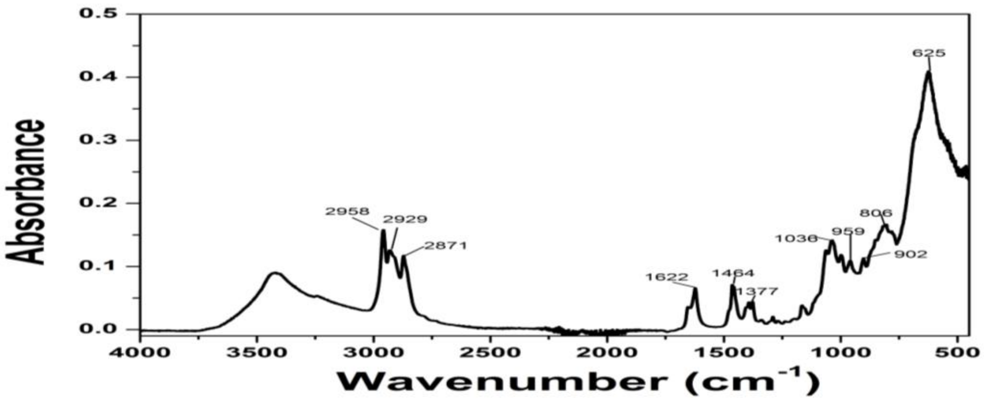


Lewis base	Lewis acid	Acid-base ratio	Mg cycling efficiency	Electrolyte decomposition potential
Bu_2Mg	$AlCl_2Et$	1-2.00	95	2.10



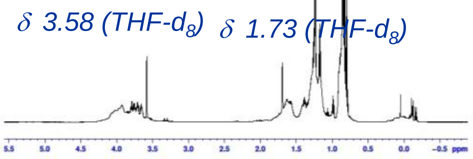
Aurbach et al. J. Electrochem Soc., 149 (2), (2002), A 115-21

Analysis of $Mg(AlCl_2BuEt)_2$ complex salt by FTIR and NMR

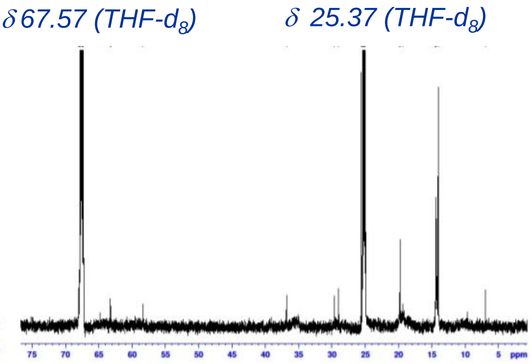


FTIR measurement was conducted using a Nicolet Model 6700 spectrometer

C-H stretch at 3000-2875 cm^{-1} (alkyl groups/ alkanes)
CH_2 bending absorption at 1464 cm^{-1} and CH_3 bending at 1379 cm^{-1}
Mg-Cl bond ~ 625 cm^{-1}



Proton (^1H) NMR



Carbon (^{13}C) NMR

NMR spectra acquired using Bruker® 700 MHz NMR spectrometer

For NMR analysis ~ 5 mg $Mg(AlCl_2BuEt)_2$ powder sample was dissolved into 0.5 ml deuterated THF (d_8) solution

Chemical shifts of the alkyl function groups n-butyl:
^1H δ -0.59, 0.9, 1.29, 1.57
sec-butyl: ^1H δ -0.3, 0.99, 1.59, 1.67

Group of peaks observe due to spin-spin coupling of neighboring protons

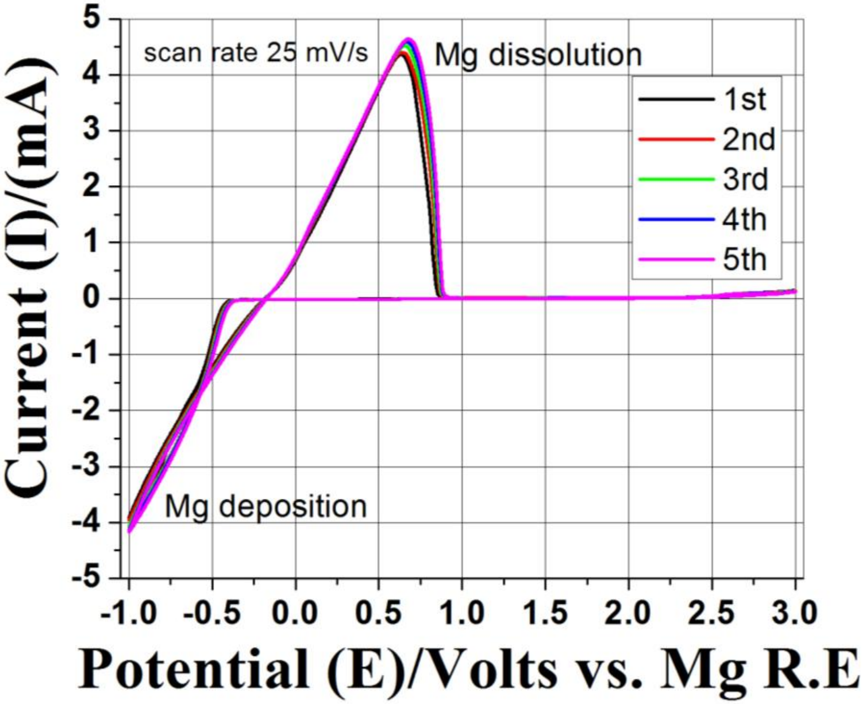
Chemical shifts of the alkyl function groups
n-butyl: ^1H δ 7.98, 14.4, 32.29, 33.83
sec-butyl: ^1H δ 17.4, 20.63, 22.5, 34.11

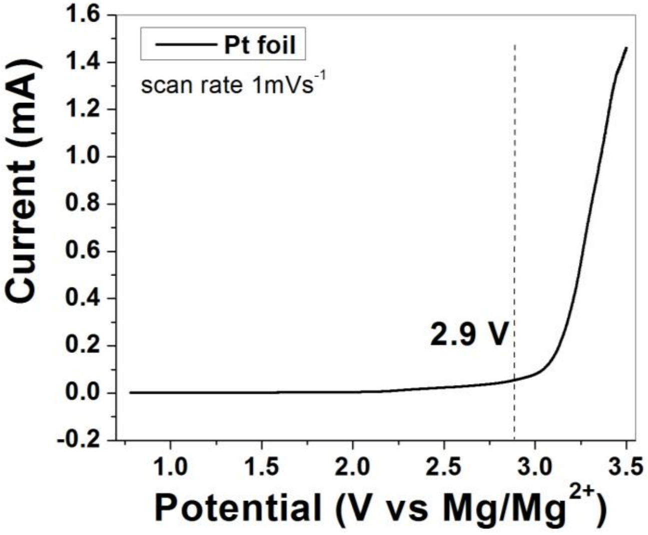
2(PhMgCl)-$AlCl_3$ based 2nd generation non-aqueous electrolyte (potential window ~ 3 V)

LSV confirms the electrochemical window ~ 2.9 V (Pellion Tech also observed ~ 2.9 V)

Coulombic efficiency ~ 90%

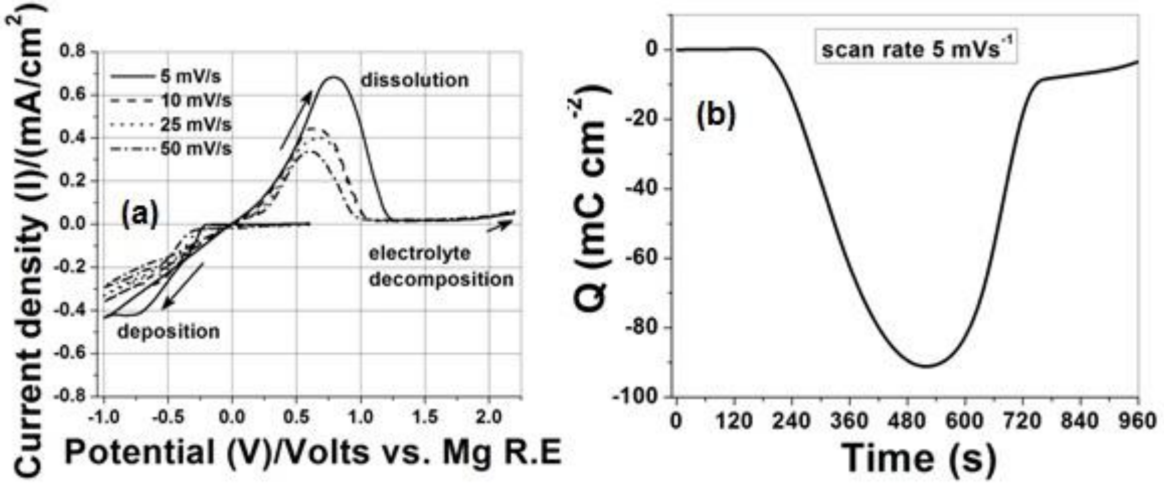
Reversible electrochemical deposition/dissolution of magnesium observed within -1 V to 3 V potential window respect to Mg reference electrode





Scan rate (5mV/s)	Onset deposition potential (V)	Anodic stripping peak potential (V)	Mg cycling efficiency (%)
cycle 1	-0.37	0.643	85.5
cycle 2	-0.363	0.648	86.5
cycle 3	-0.355	0.66	87.1
cycle 4	-0.347	0.671	87.6
cycle 5	-0.333	0.681	88.0

Developed novel electrolytes based on the amido metal-Mg halide complexes of Mg in 1.0 M THF



Scan rate (mV/s)	Onset deposition potential (V)	Anodic stripping peak potential (V)	Mg cycling efficiency (%)
5	-0.191	0.682	90.78
10	-0.192	0.693	64.29
25	-0.243	0.686	64.25
50	-0.293	0.645	56.89

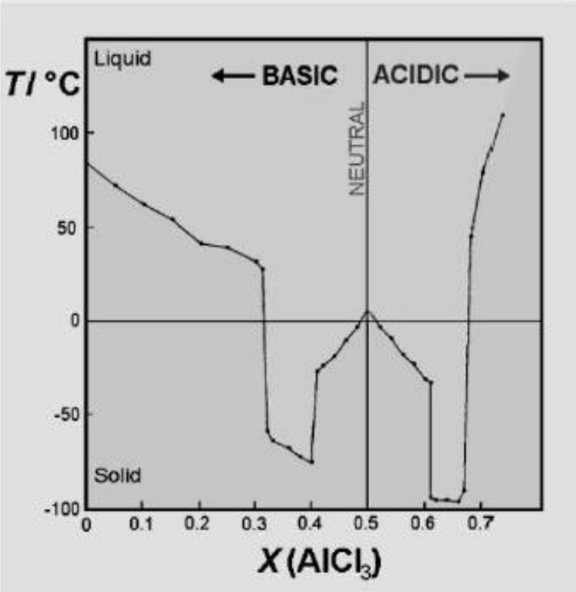
Transmetallation with a Lewis acid ($AlCl_3$) will be performed to improve the anodic stability

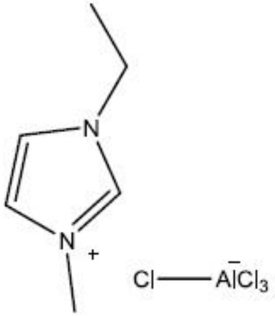
The present Lewis base holds considerable promise and have the potential for developing high voltage (~4 V) next generation electrolytes

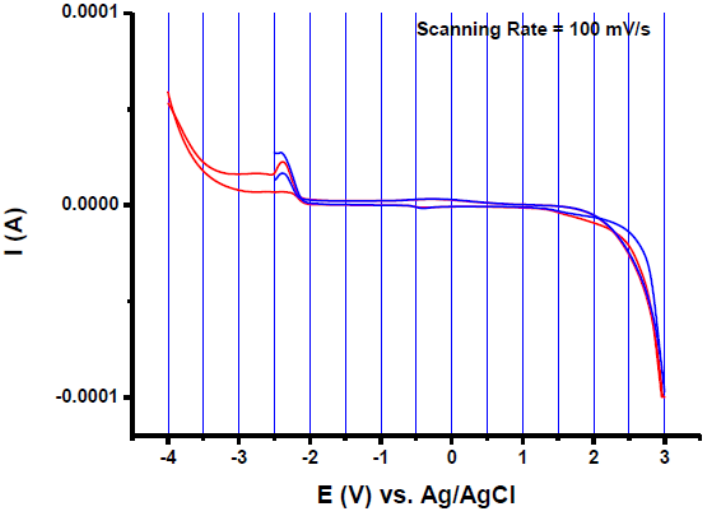
Electrochemical window/anodic stability ~ 2 V

Development of Ionic Liquid (IL) based Mg Electrolytes

Approach

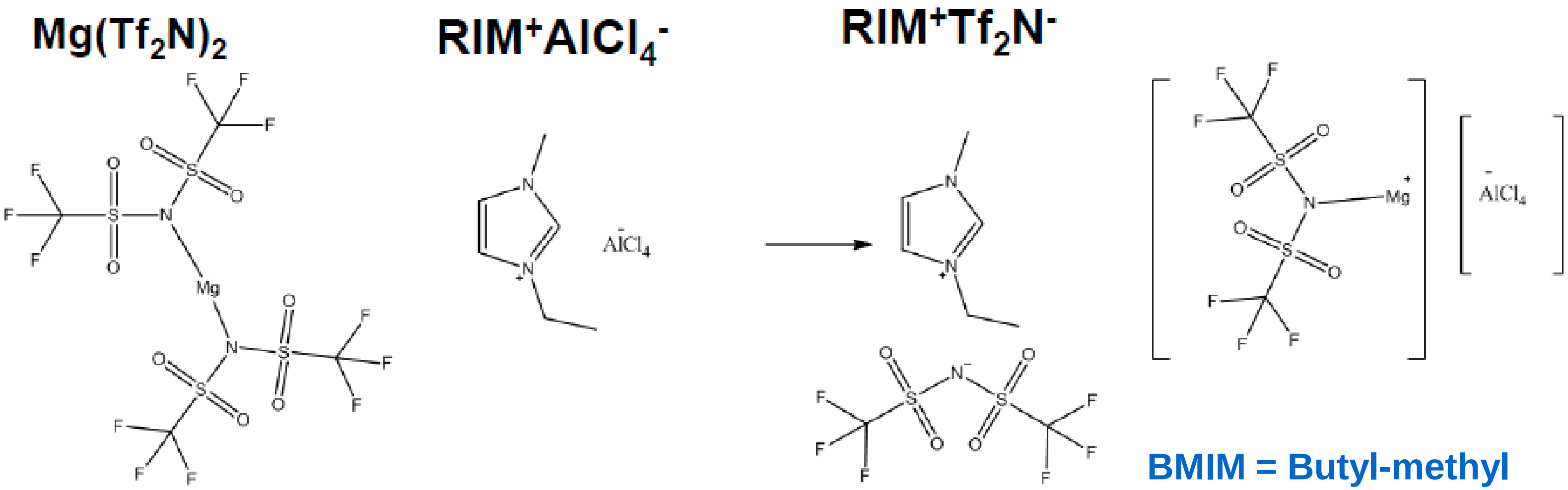






- **AluminoChlorate based ILs have the potential to perform transmetallation reactions with Mg**
- **AluminoChlorate can be basic, neutral or acidic ($AlCl_3$ conc.)**
- **Large Potential window (4V)**
- **Excellent thermal stability (> 250 °C)**
- **Excellent electrochemical stability**

Approach: IL assisted transmetallation reaction



BMIM = Butyl-methyl imidazolium Chloroaluminate (If it is an $AlCl_4^-$ anion)

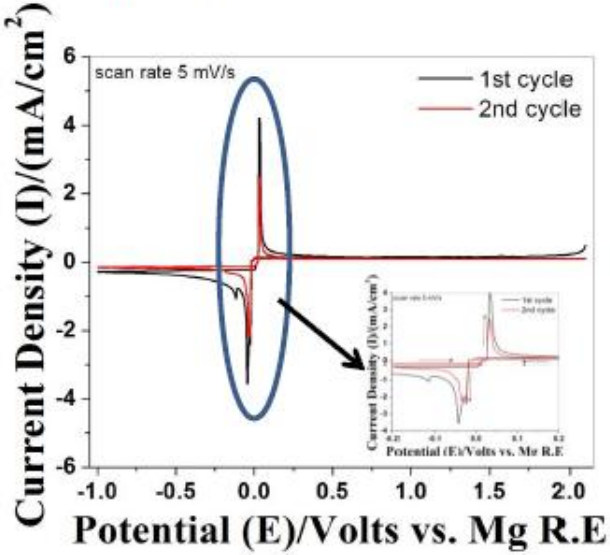
$Mg(Tf_2N)_2$= Magnesium salt of Bis-trifluorosulfonamide

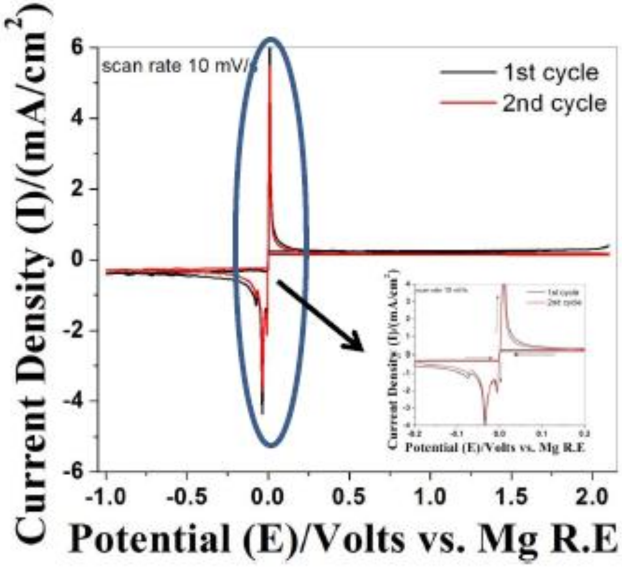
- **Ionic nature of ILs promotes transmetallation reaction**
- **Currently several types of ILs/solvent mixtures are being evaluated**

Cyclic voltammetry of Mg $(TF_2N)_2$ in THF

Electrolyte prepared by dissolving the IL into dry THF (0.25 M^{-1}basis)

Cyclic voltammetry conducted in a 3-electrode cell using Pt as W.E. and Mg foil being C.E. and R.E. (potential window of -1 to 2.1 V)



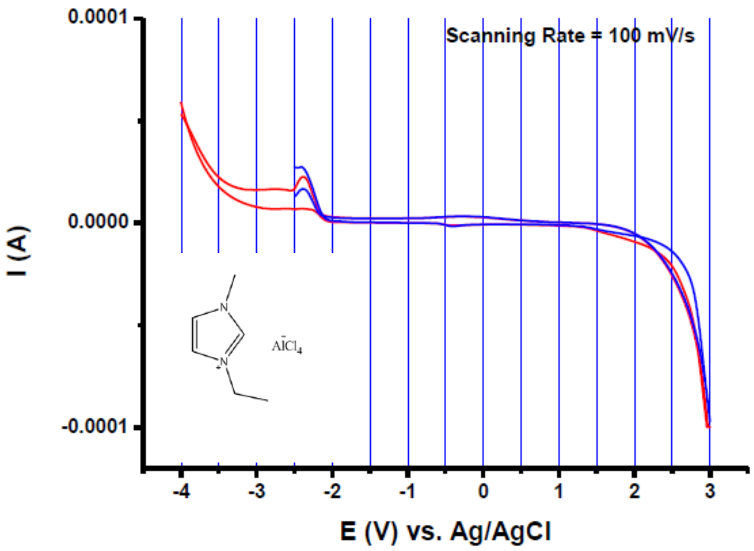


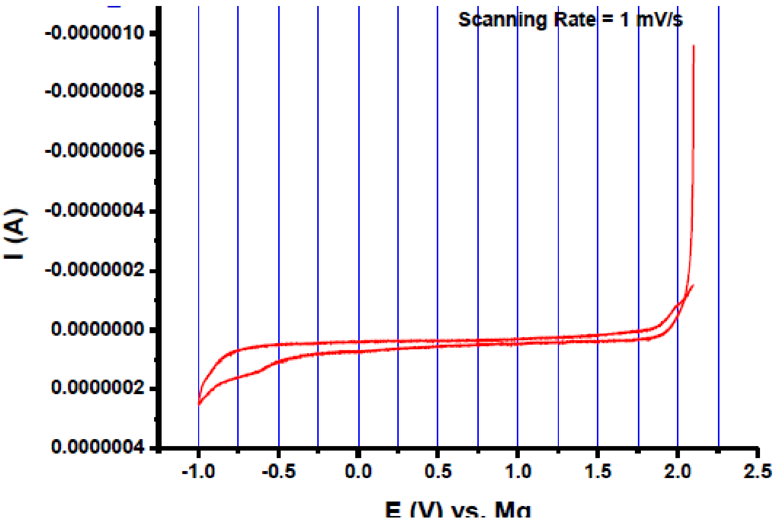
Initial test was performed on Mg $(TF_2N)_2$ in THF.

Reversible dissolution/ deposition of Mg was observed

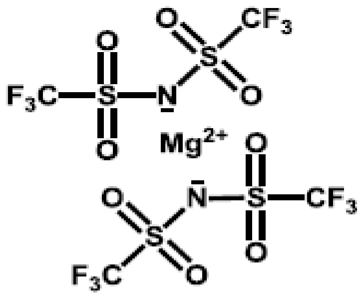
Results

- $BMIM^+ AlCl_4^-$ has a potential window of 4V
-
- No Mg deposition occurs with $Mg(TF_2N)_2$ in BMIM TF_2N ionic liquid
- Likely TF_2N anion in IL binds tightly to the Mg in this system





Assisted transmetallation: Proof of concept



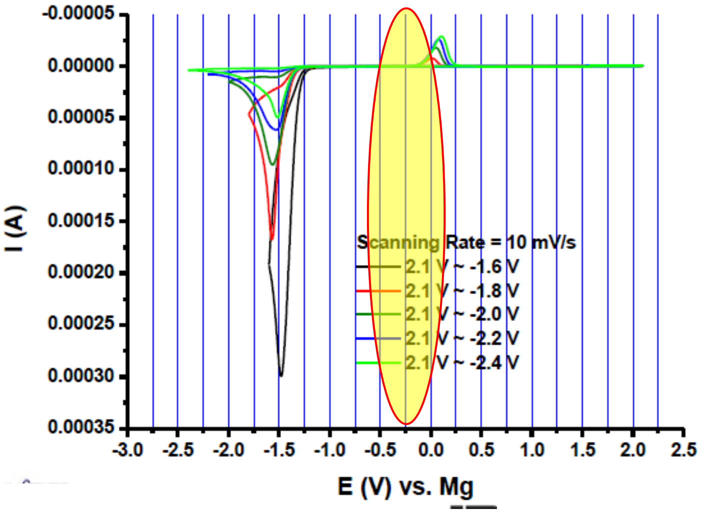
$Mg(Tf_2N)_2$

$BMIM^+AlCl_4^-$

Molar ratio $Mg(Tf_2N)_{20}$ / $BMIM^+AlCl_4^-$ = 1/50
$[Mg(Tf_2N)_2]_0$~ 0.1 M

$[Mg(TF_2N)_2]$= 0.1 M in $BMIM^+ AlCl_4^-$:THF (1:1) shows deposition/dissolution

Solubility of $Mg(TF_2N)_2$ in $BMIM^+ AlCl_4^-$ is an issue



Summary

- **Successfully synthesized Mg($AlCl_2BuEt$)$_2$/THF (0.25 mol L^{-1}) based 1st generation electrolyte, coulombic efficiency close to 99% which is in excellent agreement with the literature value of 95% [**Aurbach et al. J. Electrochem Soc. 149(2), (2002), A115-121]

- **Successfully synthesized 2(PhMgCl)-$AlCl_3$ based 2nd generation electrolytes which show electrochemical stability upto 2.9 V vs. Mg/Mg^{2+}**
  Coulombic efficiency close to 90%

- **Potential new electrolyte identified and will be further developed with potential window ~ 4 V**

- **Cyclic voltammetry of Mg(Tf_2N)$_2$/THF IL based electrolyte shows Mg can be reversibly deposited onto the Pt electrode. Further improvements are needed**

- **Showed proof of concept for the assisted transmetallation reaction in $BMIM^+$ $AlCl_4^-$:THF system**

Summary

- Pt, Ti, Ni are the potential candidate which remain inert in the electrolyte
- Mg cyclic efficiency on Ni foil is close to 99% whereas Cu is close to 88%
- LSV study using 1st generation electrolyte onto commercial graphite foil (Alfa Aesar: 130 μm) show improved anodic stability (~ 0.43 V) than Grafoil®
- Developed novel Mg-compound by RSP (sp. capacity is 26% better than pure Mg), can act as potent alternative anode for Mg battery system. Cyclic voltammogram of the new Mg-anode shows the redox couple within 0-1 V
- Developed various Mg oxides, sulfides silicate compounds as potential insertion host for Magnesium. Few compounds are indentified as potential candidate where Mg2+ ion can be reversibly cycled.
- Scope to improve the materials chemistry to reduce irreversible loss, capacity fading and discharge capacity. Attempt will be made to develop the in-situ carbon composite material to improve electronic conductivity and hence sp. capacity further

Future Work

- Ni and graphite foil has already been identified as suitable current collectors for Mg batteries which display excellent anodic stability. Electrochemical tests will be performed to check the feasibility an stability of the current collectors for long cycles (> 1000 cycles)

- Explore other novel corrosion resistant Mg-alloys with better sp. capacity than pure Mg as an alternatives for Mg anode system

- Various novel intercalation chemistries in 3-D, porous network will be explored via different synthesis routes (soft template, CVD, PLD, *in-situ* graphene composites etc.) in bulk form to improve Mg^{2+} ionic transport, minimize the polarization effect and improve sp. capacity for longer cycles

- Develop novel electrolyte with improved electrochemical stability window (~ 4 V)

- Evaluate other Grignard based systems for generating novel, stable organic electrolytes

- New Lewis acid ionic liquids currently being synthesized will be targeted to have higher solubility for $Mg(Tf_2N)_2$

"As Knowledge Increases, Wonder Deepens"

Charles Morgan; 1894-1958; English writer

Thank You For Your Attention