Docket #: S09-371

Nanocarbon/Inorganic Nanoparticle Hybrid Materials for Energy Storage and Fuel Cells

Researchers in Prof. Hongjie Dai's laboratory have combined graphene with metals and other inorganic elements to create a variety of hybrid materials that can be used for high performance electrocatalytic or electrochemical devices such as batteries and fuel cells. One type of hybrid material is formed from nanocrystals grown on graphene nanoplates or nanorods. This material is designed for use as an electrode for fast, efficient energy storage and conversion. Another type is formed from nanocrystals grown on reduced graphene oxide to produce high-performance, bi-functional catalysts for oxygen reduction reaction (ORR) and oxygen evolution reaction (OER). A third type is a unique ORR catalyst formed from carbon nanotube-graphene complexes.

The inventors have demonstrated the technology in the following applications:

- **Pseudocapacitor materials** - Ni(OH)2 nanocrystals grown on graphene sheets showed a specific capacitance of ~1335 F/g at charge and discharge current density of 2.8 A/g and ~953 F/g at 45.7 A/g with excellent cycling ability.
- **High capacity anode for Lithium Ion batteries** - Mn_3O_4 on reduced graphene oxide showed specific capacity up to ~900 mAh/g with good rate capability and cycling stability.
- **ORR/OER catalyst** - Co_3O_4/N-doped graphene that has catalytic activity similar to platinum but with superior stability in alkaline solutions. This material also has high OER activity. The unusual catalytic activity arises from synergetic chemical coupling effects between Co_3O_4 and graphene.
- **ORR catalyst** - Carbon nanotube-graphene complexes with small amounts of irons and nitrogen impurities have high ORR activity and superior stability in

acidic solution; and in alkaline solution this material shows a ORR activity that closely approaches that of platinum.

Ultrafast Nickel-Iron battery - $Ni(OH)_2$/multiwall nanotube and FeOx/graphene electrodes increased charging and discharging rates nearly 1000x over traditional Ni-Fe batteries. The battery can be charged in ~2 min. and discharged within 30s to deliver a specific energy of 120 Wh/kg and specific power of 15kW/kg.

Zinc-air battery - An electrode with CoO/carbon nanotube hybrid ORR catalyst and Ni-Fe-layered double hydroxide OER catalyst had higher catalytic activity and durability in concentrated alkaline than platinum and iridium catalysts. The battery had peak power density ~265 mW/cm^2, current density ~200 mA/cm^2 at 1 V, and energy density of >700 Wh/kg; with unprecedented small charge-discharge voltage polarization of ~0.70 V at 20 mA/cm^2 with high reversibility and stability over long charge and discharge cycles.

Stage of Development:

The technology has been applied in various devices with promising results

Please see related docket S11-094.

Applications

- **Batteries**
- Fuel Cells
- Supercapacitors

Advantages

- **High performance** - high energy densities, high power densities, ultrafast charge/discharge rates, high catalytic activity
- **Low cost** - materials made from graphene, nanotubes and common metals are much less expensive than precious metals (such as platinum and iridium)
- **Scalable**
- **Environmentally friendly** materials that can be used with safe electrolytes (such as water and potassium hydroxide for the nickel-iron battery)
- **Durable catalysts** in both acidic and alkaline electrolytes

Publications

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- Hailiang Wang, Yongye Liang, Ming Gong, Yanguang Li, Wesley Chang, Tyler Mefford, Jigang Zhou, Jian Wang, Tom Regier, Fei Wei & Hongjie Dai An ultrafast nickel–iron battery from strongly coupled inorganic nanoparticle/nanocarbon hybrid materials, *Nature Communications* 3, Published 26 June 2012.
- Stanford scientists develop ultrafast nickel-iron battery *Stanford Report* June 26, 2012.
- Yanguang Li, Wu Zhou, Hailiang Wang, Liming Xie, Yongye Liang, Fei Wei, Juan-Carlos Idrobo, Stephen J. Pennycook & Hongjie Dai, An oxygen reduction electrocatalyst based on carbon nanotube–graphene complexes, *Nature Nanotechnology* 7, 394–400 (2012). Published online 27 May 2012.
- 'Unzipped' carbon nanotubes could help energize fuel cells and metal-air batteries, Stanford scientists say, *Stanford Report*, May 29, 2012.
- Yanguang Li, Ming Gong,Yongye Liang,Ju Feng,Ji-Eun Kim,Hailiang Wang, Guosong Hong, Bo Zhang & Hongjie Dai, Advanced zinc-air batteries based on high-performance hybrid electrocatalysts *Nature Communications* 4, Article number: 1805 Published 07 May 2013.
- Stanford scientists develop efficient zinc-air battery *Stanford Report* June 4, 2013.

Patents

- Published Application: 20120214068
- Issued: 9,236,197 (USA)

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