Statement of Research Interests/Plan

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1. Previous Research Activities & Findings

My research activities were initially concerned with the development of thin film semiconductors and nitrides/oxides in particular for electron field emission, high power high temperature devices, specialty sensors, and hard coatings. I was directly involved in thin films deposition processes, materials characterization, design, modeling, fabrication, and testing of elaborated structures and devices. My achievements in the field include: BN/CN/BCN materials with excellent tribological properties [1]; demonstration of high temperature boron nitride diodes and different MIS structures based heterostructured BN/GaN and BN/SiC materials [2,3]; BN/CN thin films -based cold cathode applications [4], which led to fabrication of wide dynamic range functional pressure sensors [5]; local pulsed UV laser annealing of CN films [6]; X-ray induced modification of BN thin films electronic properties [7]; use of a novel multiphoton laser excitation technique to obtain higher photoconductivity (PC) signal from BN wide bandgap materials [8]; demonstration of BN for anti-reflection coating of photovoltaic devices [9] (**US20100235981**, **US9318626**); investigation of the major chemical trends in the deep-energy levels of isolated sp3-bonded substitutional native defects in BN [10]; proposition of a model based on experimental results suggesting nitrogen vacancies for n-type and boron anti-site or impurities for p-type BN films [11]; investigation of electronic band structure, charge density, density of states of most binary, and ternary, quaternary semiconductor alloys subjected to external parameters (i.e. pressure, temperature) [12-15].

In the last 10 years, I redirected my efforts towards nanomaterials design, synthesis, and characterization for the development of renewable energy materials and energy storage technologies, in particular. I engaged myself in a high energy density capacitor technology program for both high temperature and cryogenic applications [16]. Using funds from US Department of Defense, I developed and patented highly insulating boron nitride (BN) and boron oxynitride (BON) thin films to produce multilayer ceramic capacitors designed to operate safely at temperatures up to 300°C and above (**US 6570735**, **US 6939775**, **US 2010/0157509**). Using funds from US Department of Energy, I implemented the same capacitor technology to advance the silicon carbide (SiC) power electronics. The incorporated capacitor devices were in the pico- to nano-Farad range of capacitance values. Using fund from the National Science Foundation, I extended the capacitor technology program to larger farad ratings to meet the need of a wider range of applications. To that end, I explored a novel laser engineering technique to produce nanodielectric films, which are based on polymer shell coated metal nanoparticles. I have shown that embedding metallic nanoparticles into wide spectrum of polymers is a forceful and influential concept for producing high permittivity metamaterial films that can be incorporated into standard capacitor manufacturing processes. As a result, I fabricated artificial hybrids with dielectric permittivity several orders of magnitude higher than that of host polymers [17-18]. While this process is in principle very versatile and should allow generation of any nanoparticle core-shell system, its scalability to high volume and cost effective applications is very limited. Based on data in available literature and discussions with close collaborators, I have decided to switch to a wet chemistry route thus converting the process to a continuous flow for industrial scale-up. I was able to produce high permittivity core-shell nanodielectrics using dispersed silver metal nanoparticles cores in polyvinyl Pyrroldone (PVP) and Polystyrene (PS) polymers [19,20]. However, elaborated synthetic methods developed were time consuming in addition to higher processing costs. I recently reported on scalable, timesaving, and cost effective method to synthesize core-shell based artificial nanodielectrics. I showed that proper loadings of engineered oxidized aluminum ($Al-Al_2O_3$) in Polyvinylidene fluoride (PVDF) polymer provide high permittivity nanodielectrics in par with commercially available capacitor devices along with the added structural flexibility and cost-saving to the end user [21-22]. Along the same spirit to achieving higher capacitance for energy storage solution, I initiated the development of carbon based materials for electrochemical energy storage devices such as batteries and supercapacitors. I fabricated and tested a formulation of carbon nanotubes (CNT) and graphene based electrodes for lithium-ion batteries. The electrochemical analysis of first fabricated battery prototypes has shown excellent capacity and energy efficiency [23].

2. Research Plan

Storage of electrical energy remains the weak link in achieving wider use of highly intermittent renewable energy sources such as wind and solar energy. I intent to continue working on nanodielectric materials and nanostructured carbon electrodes, both, for energy storage solutions. The research goal is to achieve: 1) high permittivity $Al-Al_2O_3$ core-shell based artificial nanodielectrics using green chemistry processes 2) carbon nanostructures (CNS) based components for electrochemical batteries and ultra-capacitors technologies that are suitable for all types of electrical vehicles (HEVs, PHEVs, BEVs) and beyond.

A. Short term Plan

A.1. High permittivity Nanodielectrics

The highest capacitive density achieved with commercial polymer composite technology is in the order of 10 nF/cm^2. Achieving permittivity values K greater than 100 is difficult with the mature ceramic-filled polymer technology. Experimentally, relative K values of 70 are considered excellent for polymer/ferroelectric composites. The concept of putting metal nanoparticles instead of ceramic comes up because metals can, in principle, be thought of as the limiting case of high permittivity particles. My objective is to conduct research activity to develop high permittivity ($K>100$) $Al-Al_2O_3$ embedded artificial nanodielectrics via a process that can be scaled to outperform commercialized available capacitor devices.

A.2. Development of carbon based materials for Electrochemical Energy Storage Systems

My objective is to identify and test successful production of CNS material, their applicability in batteries and ultra-capacitors, and characterization as well as cost analysis in comparison to currently available activated carbon counterpart. CNS I tested so far consists of commercially purchased graphene, carbon nanotubes (CNT), and carbon fibers.

The above research efforts will be supported by commercially available COMSOL software in order to save time and cut down on fabrication expenses. COMSOL can handle unlimited physics combination.

B. Long term Plan

B.1. I plan to optimize the desired energetic properties of the $Al\text{-}Al_2O_3$ embedded artificial nanodielectrics material. I believe that development of nanodielectric material with giant permittivity may allow production of new ultra-capacitors to mirror electrochemical batteries in everything from laptop computer to transportation systems. In order to increase capacitance of the nanocomposite and, therefore, the storage capability, core-shell need to be uniformly distributed in the host polymer. This way we do not compromise the inter-particle spacing, which is the critical dimension for the onset of charge transport per percolation.

My research in also largely motivated by the fact that nanotechnology can make power cables and high voltage transmission circuits used more efficiently. I plan to optimize the desired energetic properties of the $Al\text{-}Al_2O_3$ embedded artificial nanodielectrics material. By increasing the endurance and enhancing the breakdown strength of the material we can meet several applications within the whole electrical industry.

To that end, I plan to: i) develop a processing strategy for polymer/nanoparticle systems by hot melt twin screw extrusion technique – moving from laboratory-scale to pilot-scale manufacturing. ii) Extend material processing and applicability to a wide spectrum of polymers.

B.2. With respect to electrochemical devices, my intention is to stay away from pristine quality carbon nanostructures made by chemical means, identify, and test successful CNS material produced by mechanical means for applicability in batteries and supercapacitors, and characterization as well as cost analysis in comparison to currently available activated carbon counterpart.

I will further my investigation into CNS and CNS-Silicon hybrid materials and fabrication methodologies which can facilitate the goal of creating a large-scale energy system that is not only cost effective, but also easily replicable and amenable to high volume manufacturing. Most researchers ignore the importance of mechanical properties in the anodes that may be the single most important property to prevent the well-known fading in specific capacity of carbon-silicon composites. I believe this technology will boost the performance and stability of the lithium ion batteries while driving the price of actual anode materials down (from $20 -$40/Kg to about $5/Kg).In parallel, I envision a collaborative computational effort and an empirical study that could be useful to the community in general for achieving performance closer to theoretical limits in CNT based electrochemical energy storage devices. The ultimate goal is to fabricate electrode/electrolyte materials that will enable both batteries and ultra-capacitors to meet power requirement for electrification of the transportation system. **To that end, my vision is to manufacture CNS from carbon soot (<$1/Kg) or as byproduct from large scale milling of abundant graphite. This may offer a tremendous potential as components for next generation batteries and supercapacitors which also helps create a transformative impact for grid applications.**

In summary, I will combine my experimental know-how, theoretical modeling, and meaningful simulation to build materials at the micro/nanoscale level so that new classes of micro/nanomaterials and devices could emerge to power our daily life technologies in the next 3-5 years.

I plan to transfer my existing research program to the Department of Physics at Texas Tech University. I expect my future research activities to contribute to building cross-disciplinary and cross-college fruitful collaborations.

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