# Nanotechnology Enabled Photovoltaics and Electronics for High-Power-Density Energy Systems

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## ABSTRACT

For light-duty energy systems, we examine nanotechnology-enabled high-power density micro-electronics, power electronics, energy sources and energy storage solutions. Proof-of-concept self-sustainable power systems are designed with applications in autonomous and portable aerospace, automotive, biotechnology, medical, naval, robotic, security and other systems. Practical technological solutions are considered and substantiated. We perform research and technology developments in the design of efficient and practical energy harvesting, energy management, and energy storage devices. The studied *modular* light-duty high-energy density systems consist of components and modules, such as: Low-power microelectronics; high-power-density power transistors and power electronics; enabling energy harvesting sources (solar cells and electromagnetic generators); energy storage solutions; energy management systems.

***Keywords***: electronics, energy, nanotechnology

## 1. INTRODUCTION

Affordability, competiveness, high performance, enabling capabilities, scalability, high-yield, high-power and high-energy densities, robustness and safety are ensured by nano- and micro- technologies. Enabling inorganic and organic photovoltaic cells, front-end microelectronics, innovative energy conversion and novel storage schemes are utilized. We examine high-power and high-energy densities energy systems which are designed using a *modular* taxonomy. This allows one to utilize the most advanced solutions and refine the system organization using new products and emerging technologies. These systems include energy harvesting, energy conversion and energy storage components.

Electrochemical, electromagnetic, microelectronic and electronic devices and components are enabled by using nanotechnology. New technologies imply consistent energy management which implies coherent processing, optimization and control of energy conversion. Advanced sensing and electromagnetics are achieved using nanoscaled electronics, optoelectronics and photonics [1-3]. Depending on the energy requirements and consumption, the energy sources are different. We examine light-duty energy systems which operate in the range from milli-watts to hundreds of watts with continuous and pulse energy conversion and release capabilities. The proposed design concept is applicable to portable light- and medium-duty energy systems. The system capabilities are studied in autonomous and portable applications.

## 2. *MODULAR* ENERGY SYSTEM

A broad spectrum of requirements and specifications are imposed on energy and power management systems. The energy and power densities depend on the appropriate selection of available energy harvesting, energy conversion and energy storage solutions and technologies. The physical limits on electromagnetic, electrostatic, electrochemistry, thermodynamic and thermoelectric are significant factors. To ensure optimal performance, the most advanced solutions are applied. The energy systems should meet the requirements and specifications commonly applied in advanced applications, such as MEMS, micro-systems, biomedical, etc. These systems must provide specified power during impulse and continuous operations. Energy management systems should be designed ensuring optimal energy conversion, energy management and diagnostics.

The proposed systems integrate: (1) Energy harvesting devices – Solar modules, thermoelectric or electromagnetic energy sources; (2) Power electronic module with PWM converter, filters, controllers and charger; (3) Energy storage unit – Rechargeable battery or electric double-layer capacitor; (4) Energy management system.

To solve a wide range of challenging problems, we use the most advanced nanotechnology-enabled microelectronics, energy harvesting devices and enabling hardware. Energy harvesting, power generation, controlled energy conversion, energy storage and other processes are studied. A systematic design is performed. The images of the crystal-Si and thin-film amorphous-Si *flexible* solar modules are reported in Figure 1. The rechargeable double-layer capacitors (supercapacitors) and batteries are shown in Figure 2. We examined and utilized different energy storage devices depending on system specifications and requirements. Figure 3 documents some electronic components.

Figure 4 illustrates a *modular* energy system. This system has the *Power Electronics and ICs* module which includes: Maximum power tracking controller; controlled *buck-boost* or *buck* PWM converter; sensors; filters, signal conditioning and monitoring circuitry; controllable charger which ensures optimal charging profiles depending on the energy storage devices; energy management system.

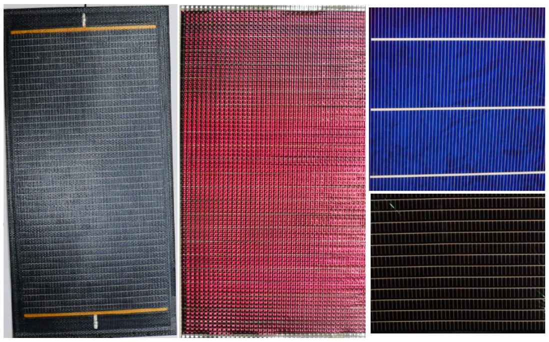

Figure 1. Solar modules fabricated using different technologies

Figure 2. Super-capacitors and lithium-ion batteries. The specific energy of existing commercial super-capacitors and hybrid capacitors varies from ~1 to 30 W-h/kg. For the rechargeable lithium-ion batteries, the specific energy reaches ~200 W-h/kg.

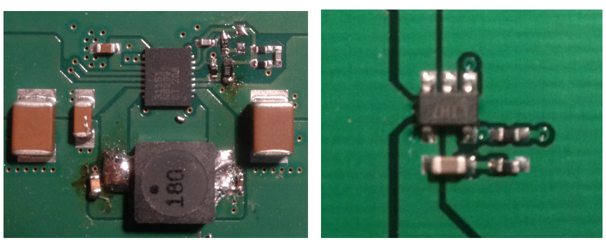

Figure 3. LTC3115 Buck-Boost PWM Converter and LTC4054 Lithium Ion Charger;

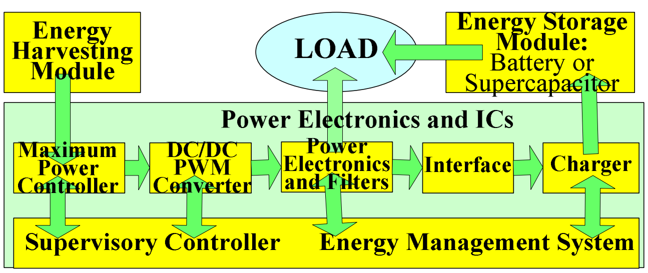


Figure 4. *Modular* organization of an energy system.

The proposed integrated energy systems are enabled by nanoscaled electronics and *modular* design. Practical solutions are found and substantiated by designing scalable power systems which guarantee the overall integrity and concurrency of power, energy management, and functionality. Device-, component- and subsystem-level solutions fully support the overall design of high-performance power generation systems with high-energy-density storage capabilities. Our optimal design is achieved by applying a modular organization within consistent topologies, enabling organization, practical topologies and coherent architecture.

## 3. Power Electronics

The main design criterion for the power electronics module is to ensure optimal conversion efficiency when operating from low to medium power photovoltaic input sources. We select and design a two-quadrant PWM converter stage which operates in the power range from 1 to 25 W. In order to provide enhanced modularity, we select the *buck-boost* topology of the power stage regulator. By implementing this topology, we are able to operate within a sufficient operating voltage and current envelope. The supercapacitor and battery modules can be charged within 3.7 V<$V_{\text{converter}}$<28 V. This provides compatibility with various single- or multi-cell lithium ion batteries. High voltage, monolithic, synchronous *buck-boost* converters are selected and tested. For example, the LTC3115 *buck-boost* converter guarantees the specified characteristics. This converter is used in various high performance and high efficiency commercial applications. It operates at input voltage sources up to 40 V, and, can provide output currents up to 2 A. Since most lithium ion battery charging solutions operate between 0.5 to 2 A output charge current, this PWM converter is compatible with the majority of applications.

Many energy systems must deal with the adverse effects of switching noise and electromagnetic interference. The selected hardware is designed to minimize radiated emissions by utilizing internal synchronous switching elements. Selecting converters with integrated MOSFETs allow the designer to minimize the radiating areas of power stage current loops and surfaces, thereby minimizing radiated electromagnetic interference and switching noise. The PWM clock circuit is synchronized to an external clock driver over a wide programmable frequency range from 100 kHz to 2 MHz. There exists an inverse relationship between switching frequency and power stage efficiency. If the PWM switching frequency is reduced, the efficiency is increased. However, this leads to the slower transient dynamics. We operate at a switching frequency ~300 kHz to achieve a balance between high efficiency and improved transient response. External clock synchronization allows the designer to isolate the cause of noise to provide targeted output filtering capabilities.

## 4. Experimental Studies and Testing

We refined and advanced the designs, components and solutions reported in [4-6]. The studied energy system includes the following modules:

1. High-efficiency (~15 to 19%), ~20 W solar modules;
2. Energy management systems with electronic and ICs components and modules;
3. Lithium ion battery and/or supercapacitors.

The image of the proof-of-concept test-bed and components are illustrated in Figures 1 to 3. Depending on the solar cell illumination, the input voltage of the solar module varies from 5 to 17 V. The output voltage of the converter is designed for $V_{\text{converter}}$=4.5 V. This design voltage was selected due to the specifications of the lithium ion management solution which requires an input operating voltage from 4.2 to 6.5 V. The system achieves near optimal efficiency with an output voltage 4.5 V. The lithium ion management system is


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designed to charge single or multiple lithium ion cells up to 4.2 V which corresponds to the standard maximum voltage of a single cell cell. The maximum charge current for the studied design is ~0.8 A. The experimental results for the system performance, loading, transient dynamics and other key performance quantities are reported in Figures 5 to 8. The efficiency varies from 92% to 95%. In Figures 5 to 8 the top, middle and bottom plots correspond to the output voltage $v_{output}(t)$, input current $i_{output}(t)$ and input voltage $v_{input}(t)$, respectively.

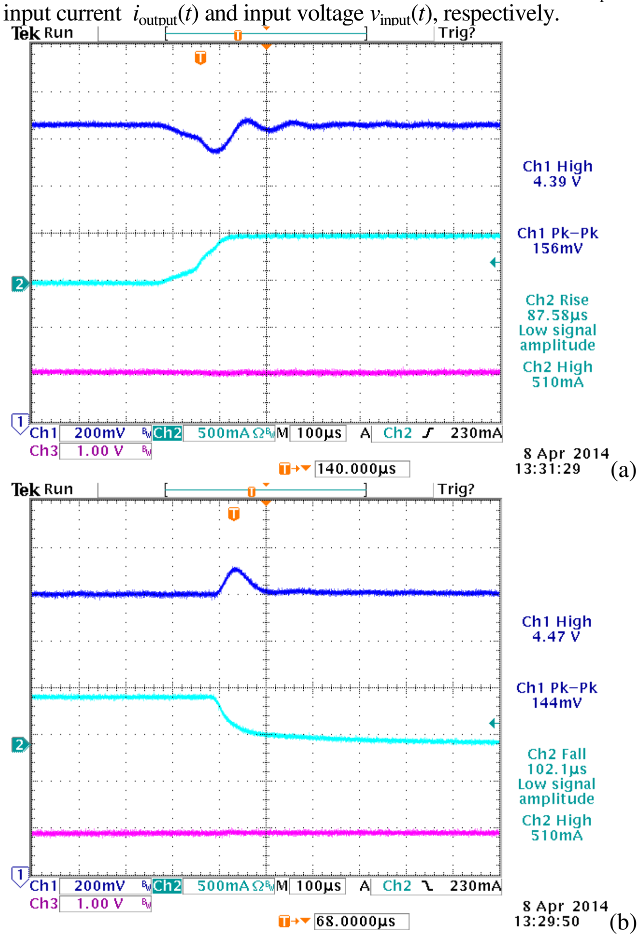
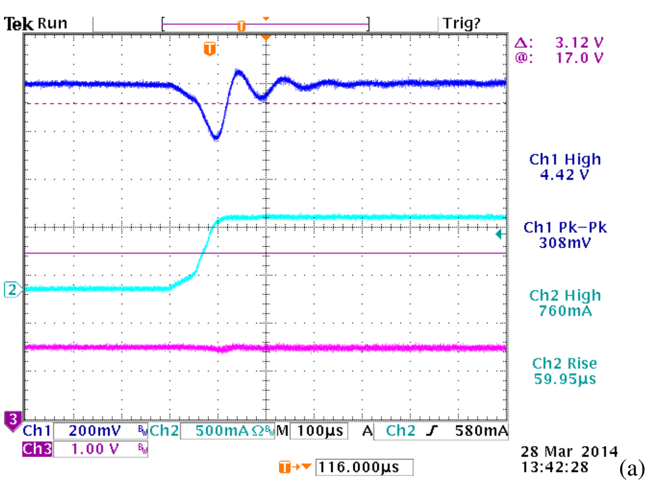



Figure 5. Dynamics of $v_{output}(t)$, $i_{output}(t)$ and $v_{input}(t)$ if $R_L$=9 ohms. The output converted voltage is stabilized at $V_{converter}$=4.5 V and $I_{converter}$=0.5 A. (a) The $R_L$ load is applied; (b) The load $R_L$ is removed.



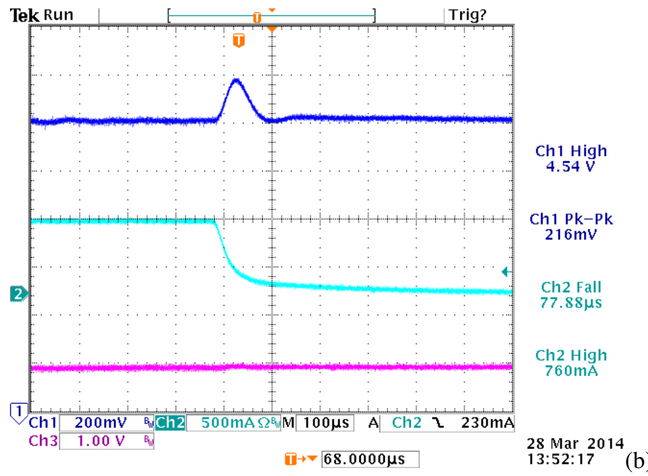




Figure 6. Dynamics of $v_{output}(t)$, $i_{output}(t)$ and $v_{input}(t)$ if $R_L$=6 ohms. The output converted voltage is stabilized at $V_{converter}$=4.5 V and $I_{converter}$=0.75 A. (a) The $R_L$ load is applied; (b) The load $R_L$ is removed.

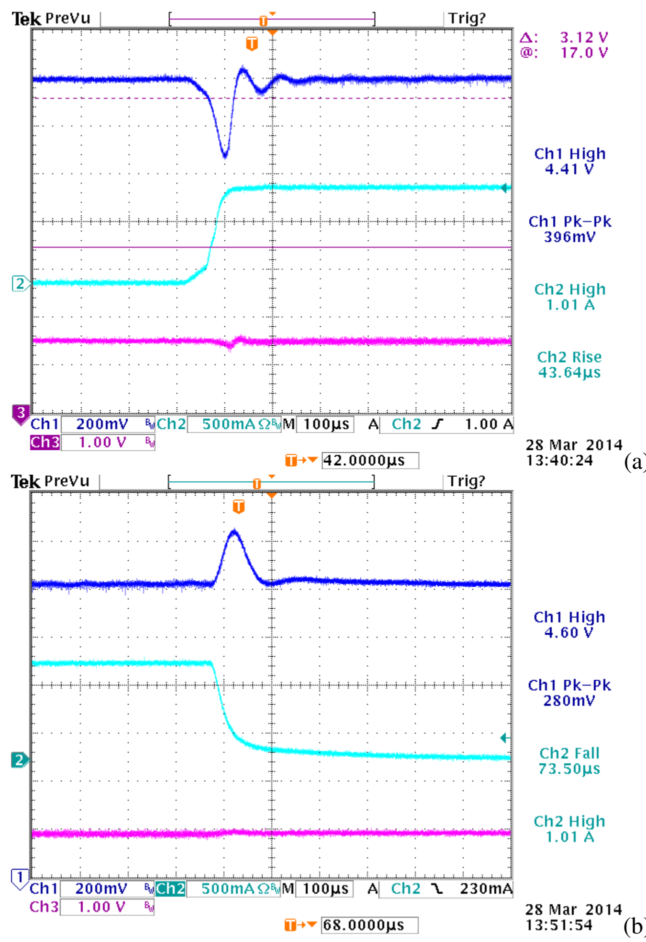
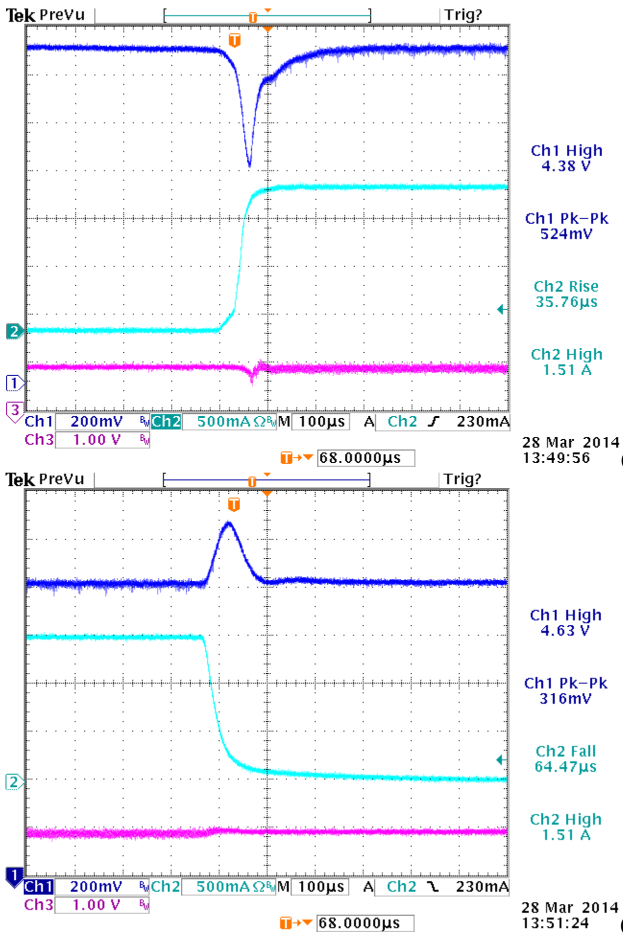



Figure 7. Dynamics of $v_{output}(t)$, $i_{output}(t)$ and $v_{input}(t)$ if $R_L$=4.5 ohms. The output converted voltage is stabilized at $V_{converter}$=4.5 V and $I_{converter}$=1 A. (a) The $R_L$ load is applied; (b) The load $R_L$ is removed.




(a)

(b)

Figure 8. Dynamics of $v_{output}(t)$, $i_{output}(t)$ and $v_{input}(t)$ if $R_L$=3 ohms. The output converted voltage is stabilized at $V_{converter}$=4.5 V and $I_{converter}$=1.5 A. (a) The $R_L$ load is applied; (b) The load $R_L$ is removed.

## 4. Conclusion

For low- and medium-duty power energy systems, we designed, verified, and demonstrated scalable proof-of-concept solutions with applications to portable renewable energy applications. We utilized advanced nanoscaled microelectronics, high-efficiency power electronics, photovoltaic and energy harvesting components and modules. The energy conversion, management and charging solutions are developed to design low-cost, high efficiency and high-power density energy systems. These systems are aimed for applications in aerospace, automotive, biotechnology, consumer electronics, industrial, medical, naval, robotic, security and other portable systems. The effectiveness and applicability of the aforementioned portable energy systems were substantiated through experiments and technology transfer developments.

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