Energy Harvesting for Microsystems

Dr. Lynn Fuller, Dr. Ivan Puchades, Priya Narasimhan

Webpage: http://people.rit.edu/lffeee
Microelectronic Engineering
Rochester Institute of Technology
82 Lomb Memorial Drive
Rochester, NY 14623-5604
Tel (585) 475-2035
Fax (585) 475-5041
Email: Lynn.Fuller@rit.edu
Department webpage: http://www.microe.rit.edu

2-2-2013 Energy_Harvesting.ppt

OUTLINE

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Power Conditioning Electronics
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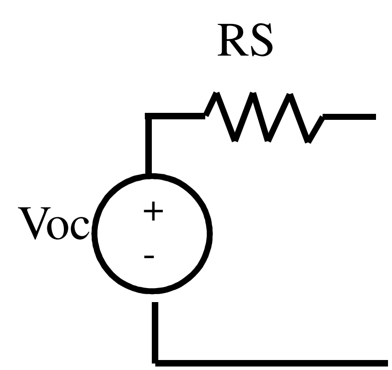
INTRODUCTION

We would like to harvest energy from the environment and store that energy in a battery or super capacitor and thus provide a long lasting power supply for wireless Microsystems. There are many sources of energy in the environment that we can use including, light, temperature difference and mechanical vibration. We also have many devices that can convert these sources of energy into voltage and current such as photovoltaic cells, thermopiles, thermoelectric generators (TEG), piezoelectric generators and electromagnetic induction devices.

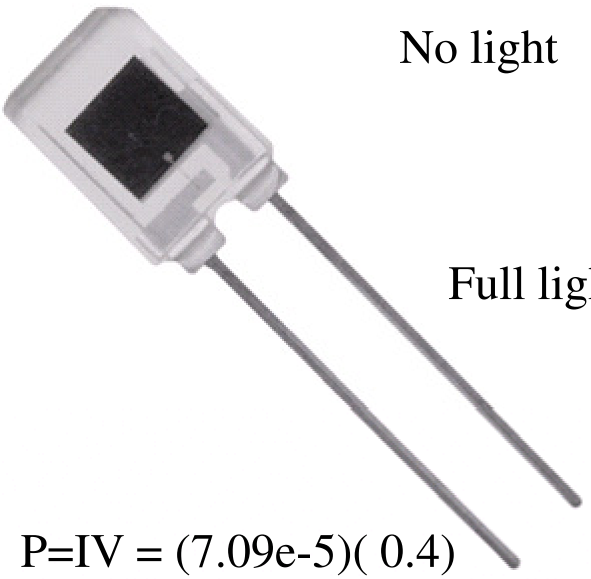
This document will investigate energy conversion devices and the power conditioning electronic circuits used between the energy conversion devices and the storage element.

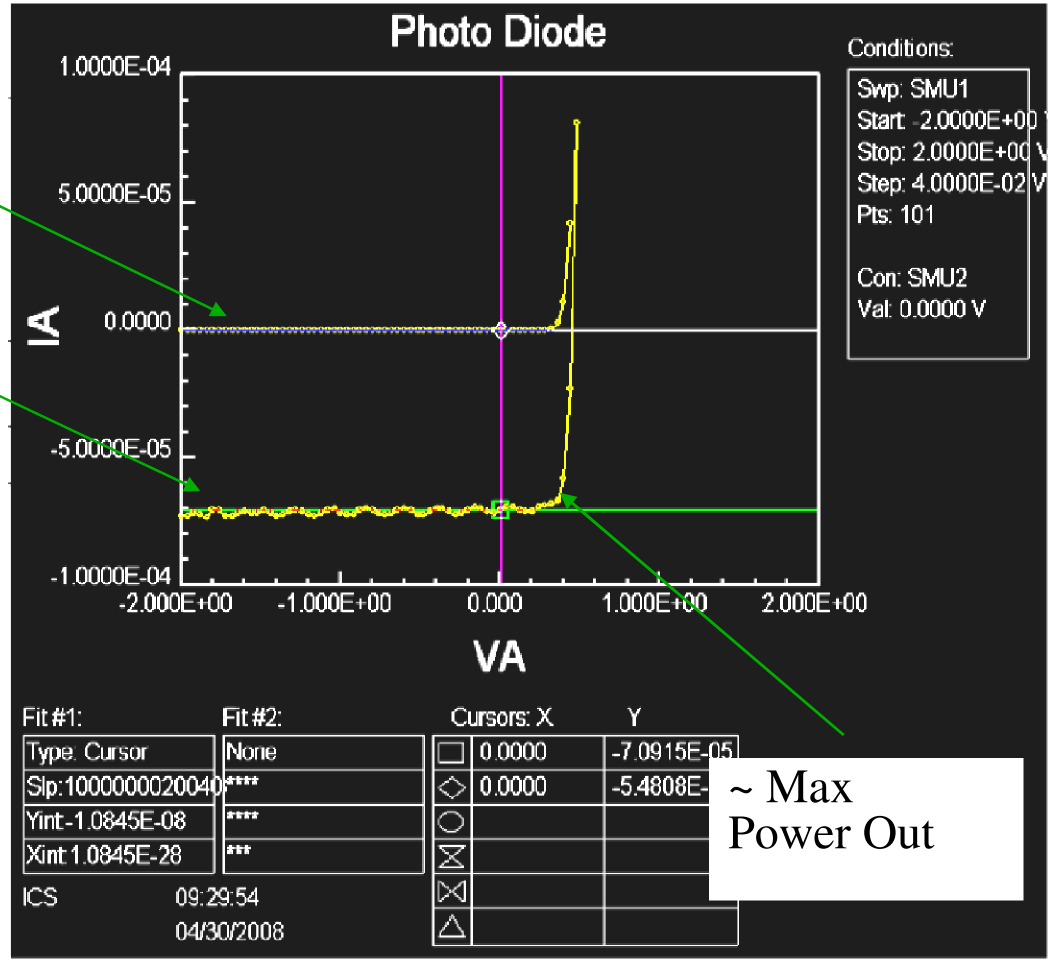
ENERGY CONVERSION DEVICES

Device Type	AC or DC	RS	Voc	Isc
Photocell	DC	Medium (100Ω)	0.5 V	Varies with size
Thermoelectric (Peltier)	DC	Low (1 Ω)	1 V	Amperes
Thermopile (Seebeck)	DC	Low (1 Ω)	100mV	Varies with size
Electromagnetic (Low Freq)	AC	Medium (100Ω)	10 mV peak	Milli Amperes
Piezoelectric (Low-Med Freq)	AC	Very High (1GigΩ)	10 V peak	Nano Amperes
RF (High Frequency)	AC	Low (1 Ω)	1 µV peak	Micro Amperes



PHOTOVOLTAIC CELL (PV)





P=IV = (7.09e-5)(0.4)

=28.4µwatts

P/unit area =

28.4e-6/1500e-6/1000e-6

= 18.9watt/m^2

No Light and Max Light Using 8X Objective Lens

SEEBECK EFFECT (THERMOCOUPLE)

When two dissimilar conductors are connected together a voltage may be generated if the junction is at a temperature different from the temperature at the other end of the conductors (cold junction) This is the principal behind the thermocouple and is called the Seebeck effect.

$$\Delta V = \alpha_1(T_{cold}-T_{hot}) + \alpha_2 (T_{hot}-T_{cold})=(\alpha_1-\alpha_2)(T_{hot}-T_{cold})$$

Where α_1 and α_2 are the Seebeck coefficients for materials 1 and 2

Thermopile (many thermocouples in series)

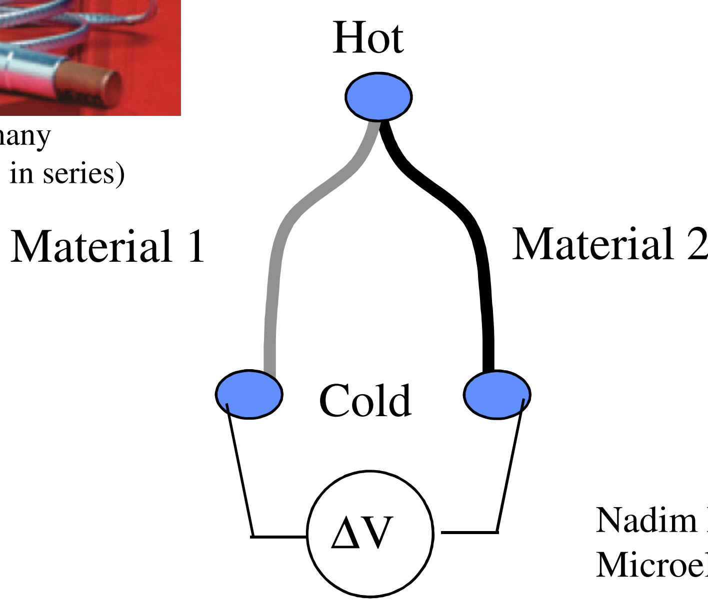


Table 2.6 The Seebeck Coefficients Relative to Platinum for Selected Metals and for *n*- and *p*-Type Polysilicon

	μV/K		μV/K
Bi	−73.4	Ag	7.4
Ni	−14.8	Cu	7.6
Pa	−5.7	Zn	7.6
Pt	0	Au	7.8
Ta	3.3	W	11.2
Al	4.2	Mo	14.5
Sn	4.2	*n*-poly (30 Ω/□)	−100
Mg	4.4	*n*-poly (2600 Ω/□)	−450
Ir	6.5	*p*-poly (400 Ω/□)	270

Note: The sheet resistance is given for the 0.38-μm-thick polysilicon films. Polysilicon is an attractive material for the fabrication of thermocouples and thermopiles because of its large Seebeck coefficient.

Nadim Maluf, Kirt Williams, An Introduction to Microelectromechanical Systems Engineering, 2nd Ed. 2004

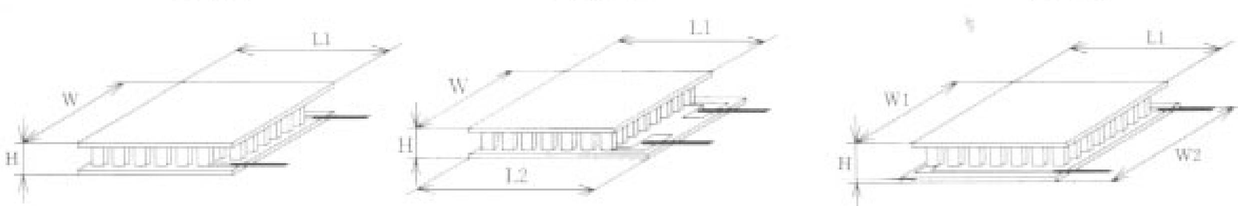
PELTIER HEAT PUMP (TEG)

Ferrotec America Corp
1050 Perimeter Rd, #202
Manchester, NH 03103
(603) 626-0700

Single Stage Coolers- Imax = 3.0 Amps

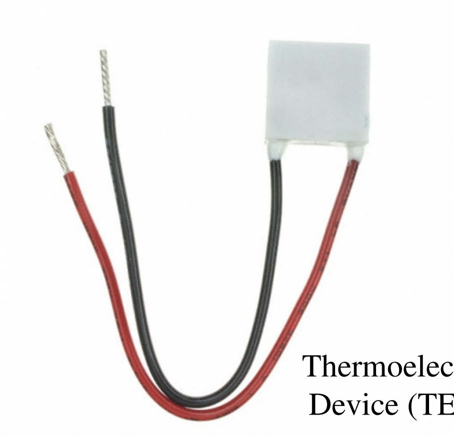
TE MODULE NUMBER			Qmax	Vmax	DTmax	Type	CONFIGURATION A			
150°C 200°C		Code	(W)	(V)	(°C)		W	L1	L	
63 or 95	01/017/030	A,B,M	3.8	2.3	72	1	11.5	11.5	–	
63 or 95	01/023/030	A,B	5.2	3.2	72	1	7.39	22.4	–	
63 or 95	01/031/030	A,B,M	7.0	4.3	72	1	15.1	15.1	–	
63 or 95	01/071/030	A,B,M	16.0	9.8	72	1	22.4	22.4	–	3.18, 3.81
63 or 95	01/127/030	A,B	29.0	17.5	72	1	29.7	29.7	–	3.94
63 or 95	01/128/030	A,B	29.0	17.6	72	2	29.7	29.7	34.0	3.94

Type 1 Type 2 Type 3

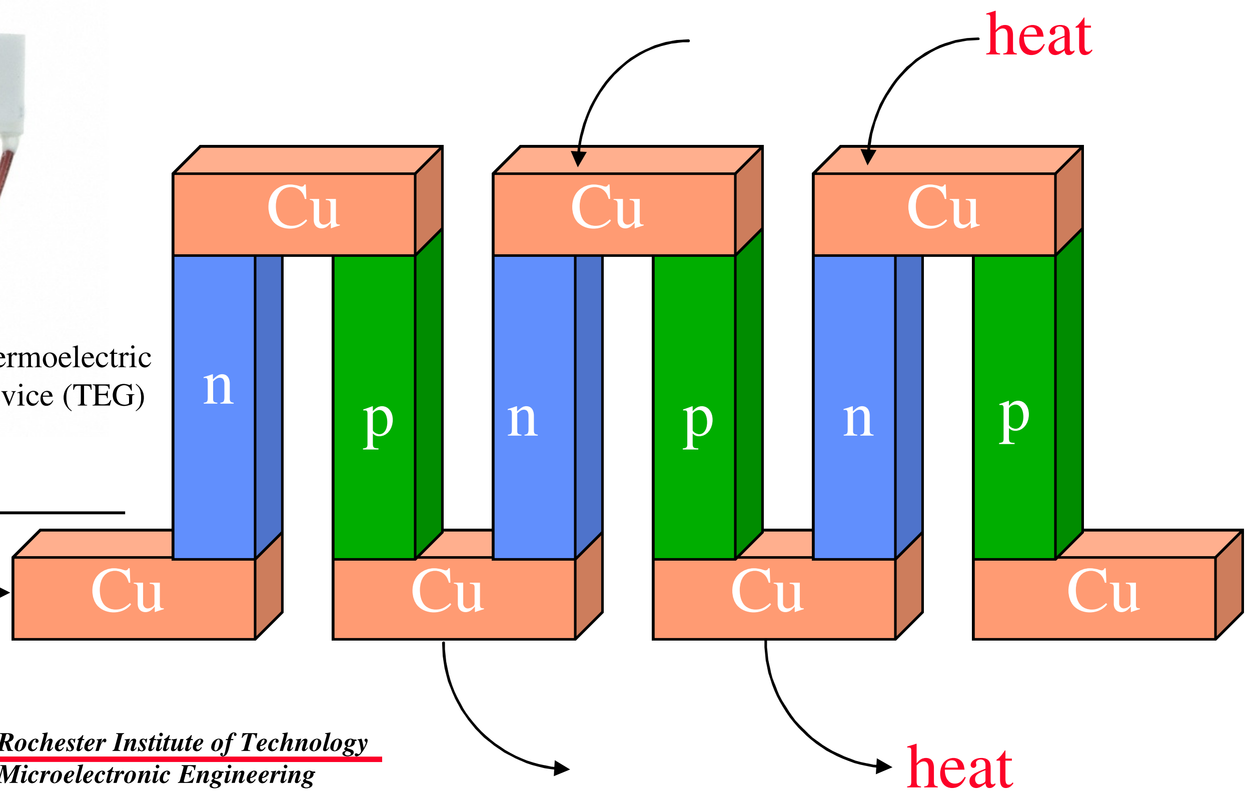


PELTIER EFFECT (TEG)

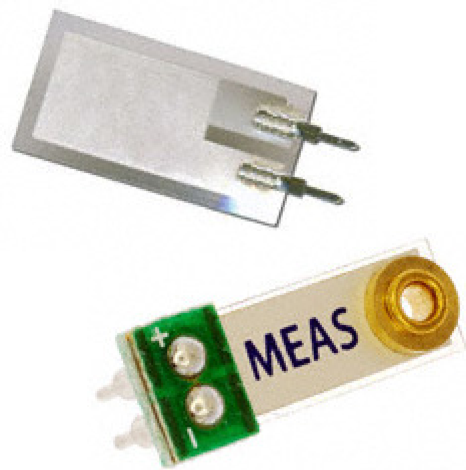
Heat pump device that works on the gain in electron energy for materials with low work function and the loss in energy for materials with higher work function. Electrons are at higher energy (lower work function) in n-type silicon.

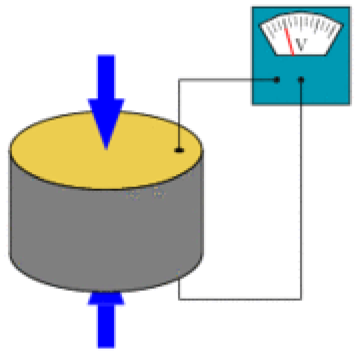


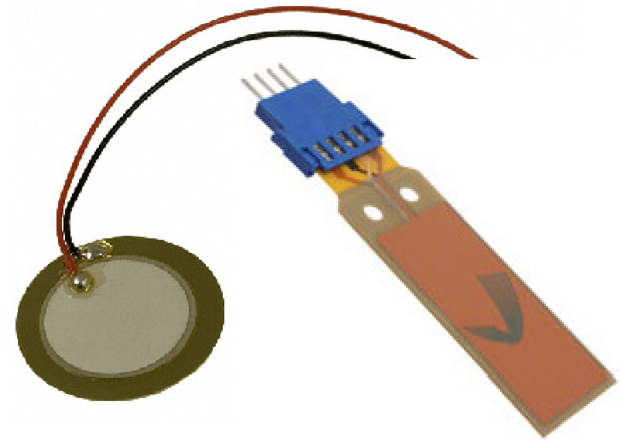
Thermoelectric Device (TEG)



PIEZOELECTRIC ENERGY HARVESTING DEVICES



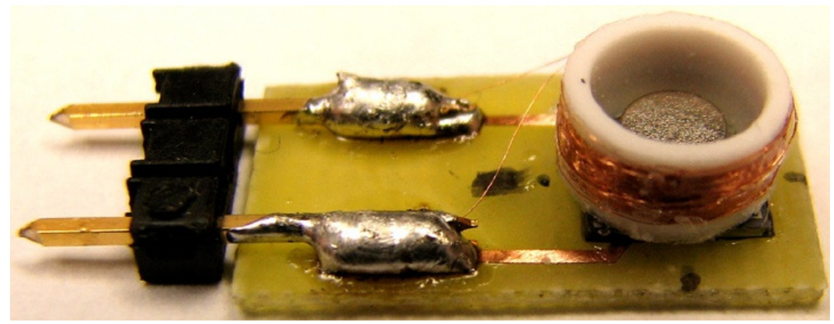


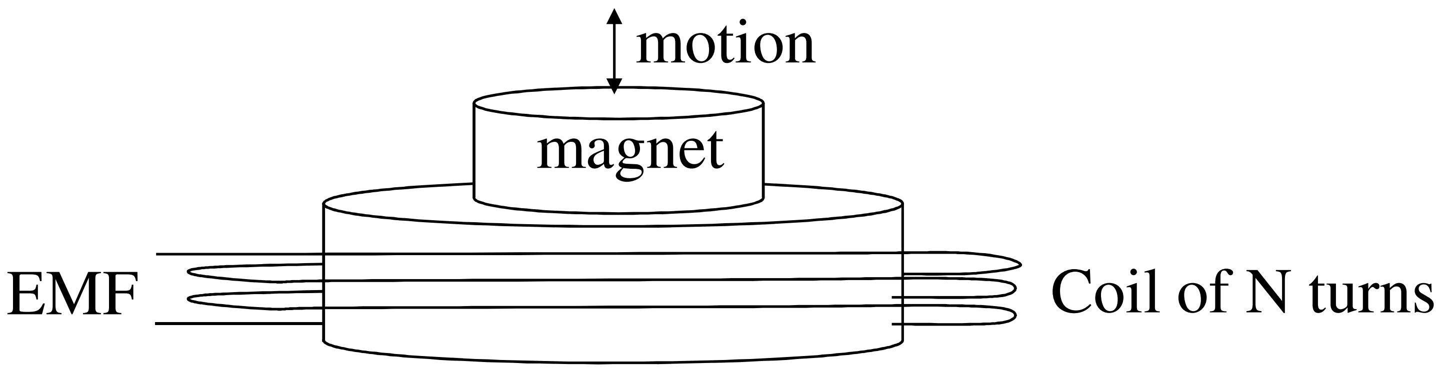


A piezoelectric material will exhibit a change in length in response to an applied voltage. The reverse is also possible where an applied force causes the generation of a voltage. Single crystal quartz has been used for piezeoelectric devices such as gas grill igniters and piezoelectric linear motors. Thin films of various materials (organic and inorganic) exhibit piezoelectric properties. ZnO films 0.2 µm thick are sputtered and annealed 25 min, 950C giving piezoelectric properties. Many piezoelectric materials also exhibit pyroelectric properties (voltage out – heat in).

ELECTROMAGNETIC GENERATORS (FARADAY)

A coil in a changing magnetic field will generate a voltage. (Faraday's Law of Electromagnetic Induction)





Faraday's Law of Electromagnetic Induction

$$EMF = -\Delta\,\Phi/\Delta\,t = -N\ Area\ \Delta\,\Phi/\Delta\,t$$

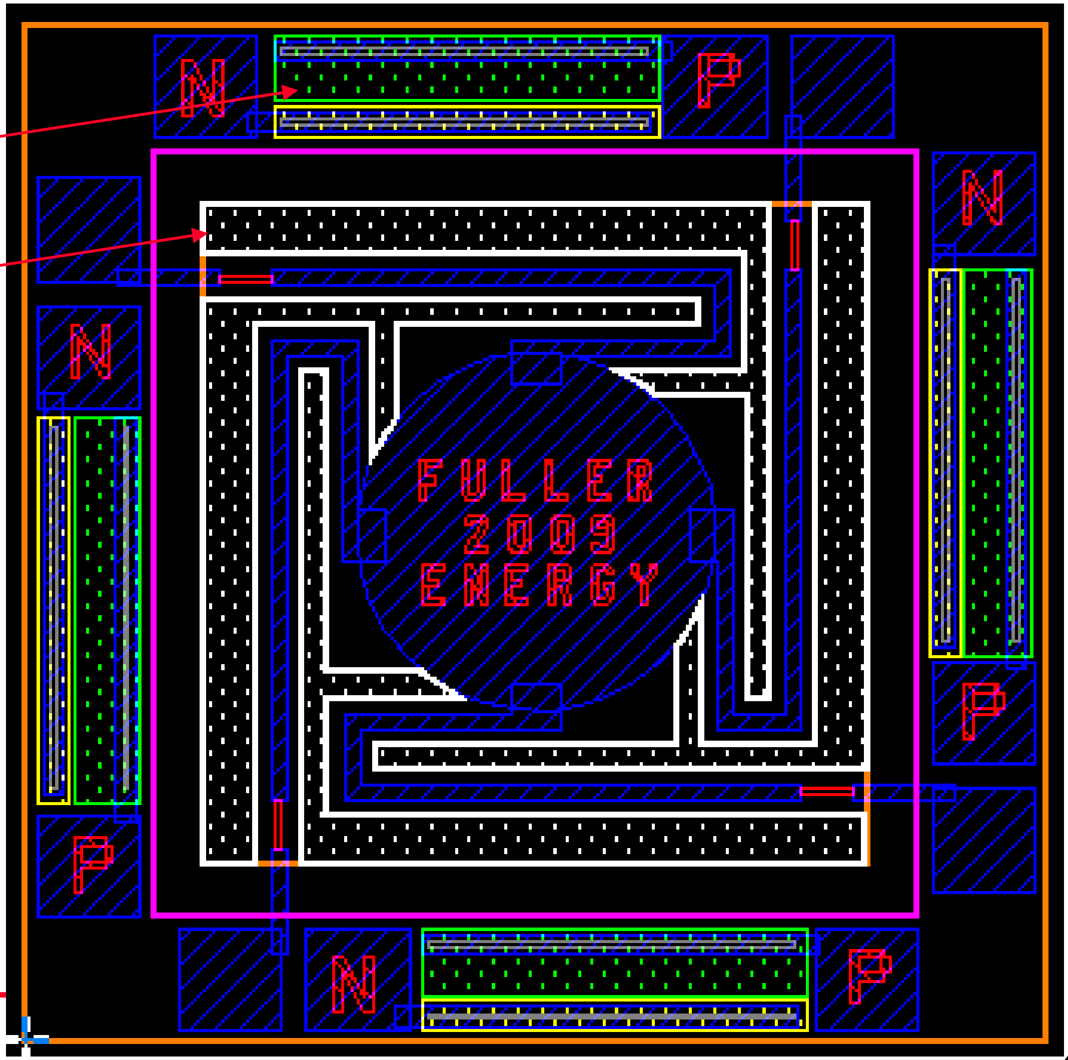
http://micro.magnet.fsu.edu/electromag/java/faraday2/

MEMS DESIGN FOR ENERGY HARVESTING

Photovoltaic Cells

The white areas end up being cut out leaving the center supported by four serpentine springs. A magnet glued to the center is supported by the spring like structure and will move in response to vibrations.

Four green photovoltaic cells also can generate energy.



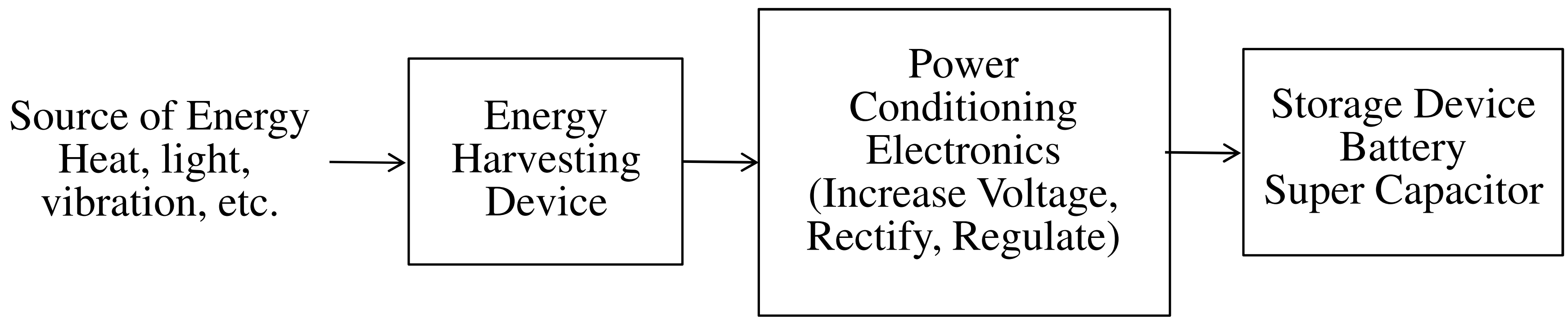
Rochester Institute of Technology
Microelectronic Engineering

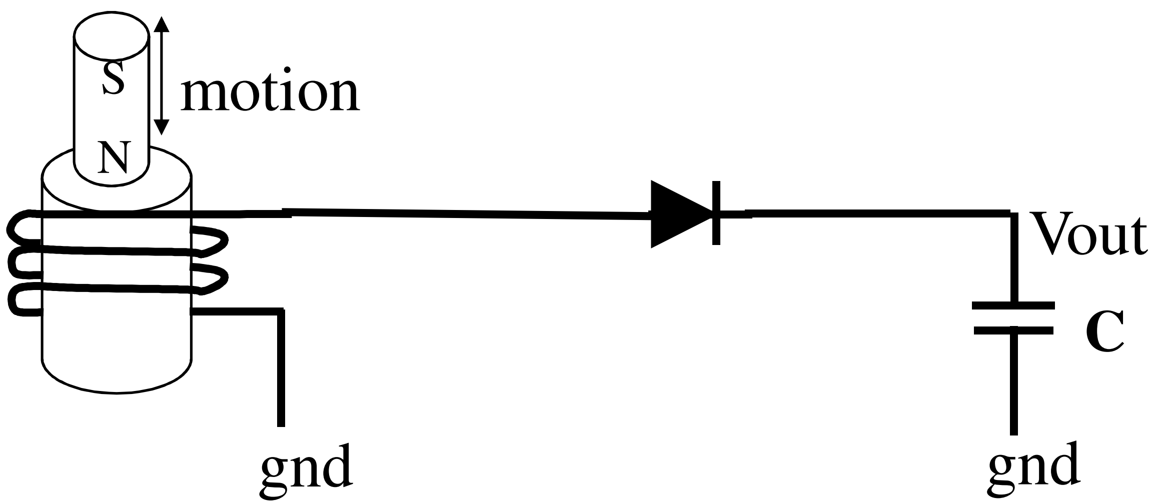
CALCULATIONS

Rochester Institute of Technology								22-Jun-08	
Dr. Lynn Fuller		Microelectronic Engineering, 82 Lomb Memorial Dr., Rochester, NY 14623							
To use this spread sheet enter values in the white boxes. The rest of the sheet is protected and should not be									
changed unless you are sure of the consequences. The results are displayed in the purple boxes.									
Solenoid in a changing magnetic field									
	Faraday's Law of Electromagnetic Induction EMF = - dΦ / dt								
EMF (Electro Motive Force) = N A ΔB/Δt				emf x Av =		-146	mVolts		
	N = number of loops			N =		450			
	r = radius of loop			r =		2	mm		
	A = area of loop			A =		1.26E-05	m2		
	B initial = Initial Magnetic Flux Density			B initial =		2123	Gauss		
	B final = Initial Magnetic Flux Density			B final =		4702	Gauss		
	t = time to go from initial to final			Δ t =		0.01	s		
	Av = Amplifier Gain			Av =		1			
Initial and Final Flux Density is from http://www.kgmagnetics.com/calculators.asp									
	10000 Gauss = 1 Tesla								

POWER CONDITIONING FOR ENERGY HARVESTING

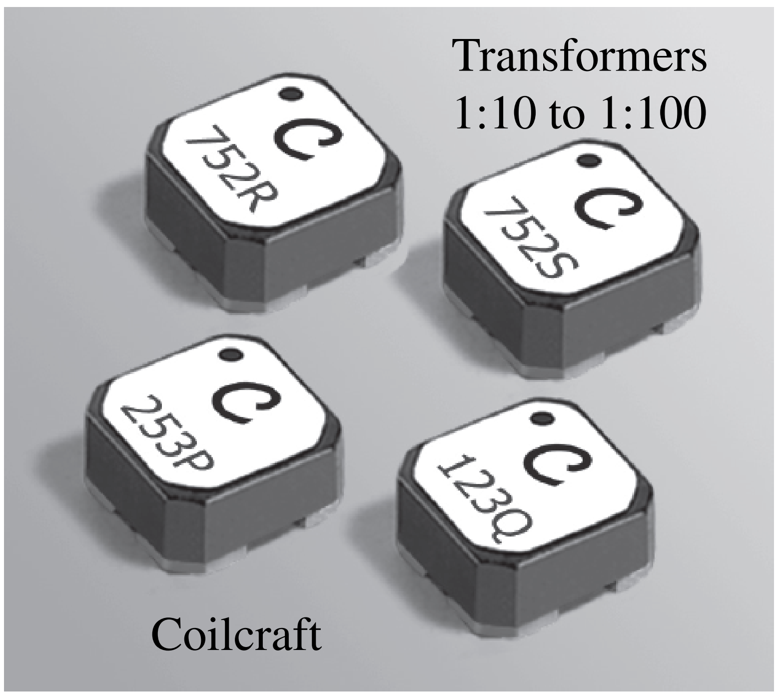
The power conditioning electronic circuits used between the energy conversion devices and the storage element will increase the voltage and convert it to DC to charge the storage element.



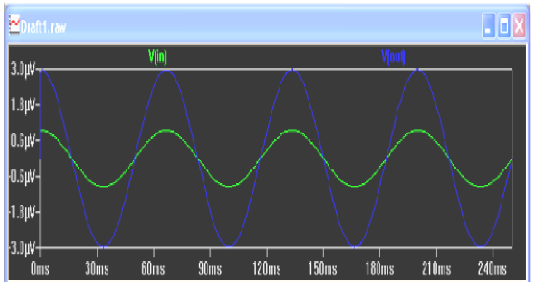


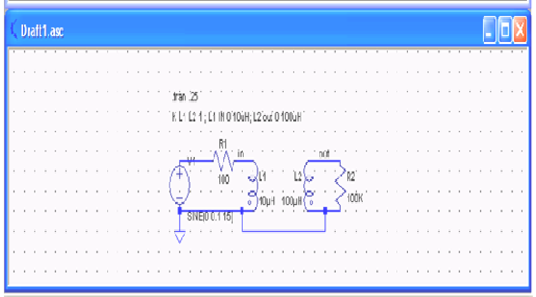
POWER CONDITIONING ELECTRONICS

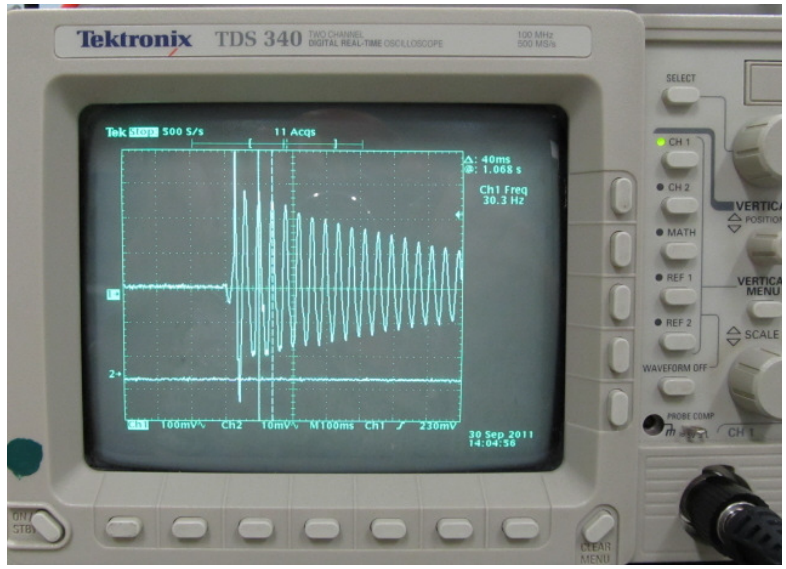
Transformers can increase the voltage for ac signals. Voltage multiplier circuits exist for AC signals. DC signals can be switched on and off and thus create changing signals in inductors and transformers that can increase the voltage. These higher AC voltages can be rectified using diodes or switches and charge a battery or super capacitor.



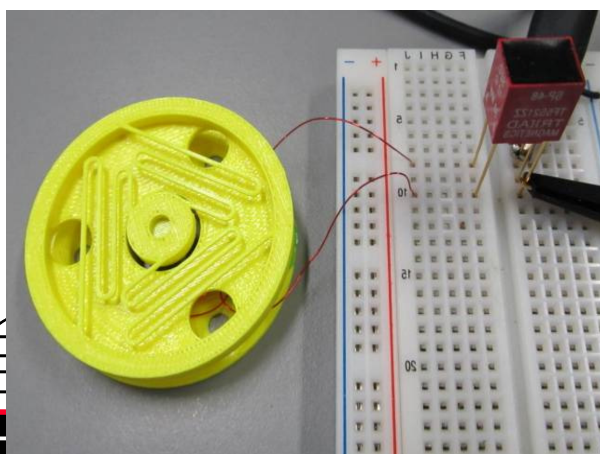
VIBRATION ENERGY HARVESTER HARDWARE

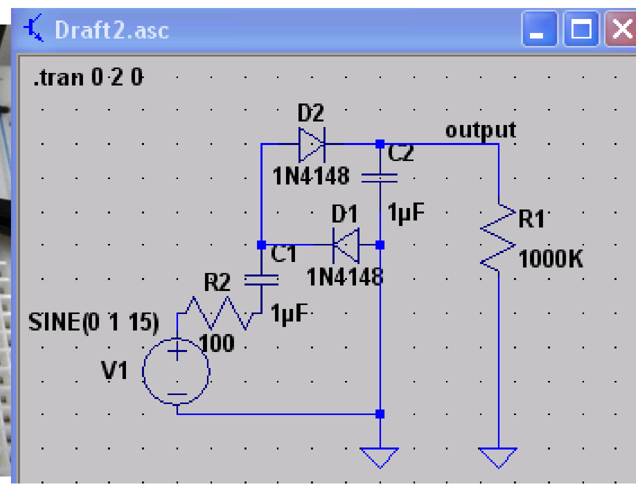


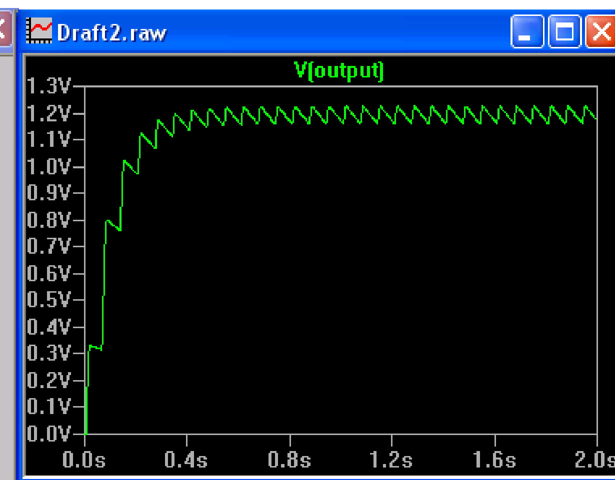




5V / 0.035F







POWER CONDITIONING (BOOST CONVERTER)

These circuits convert a low level DC (or AC) to high level DC voltage.

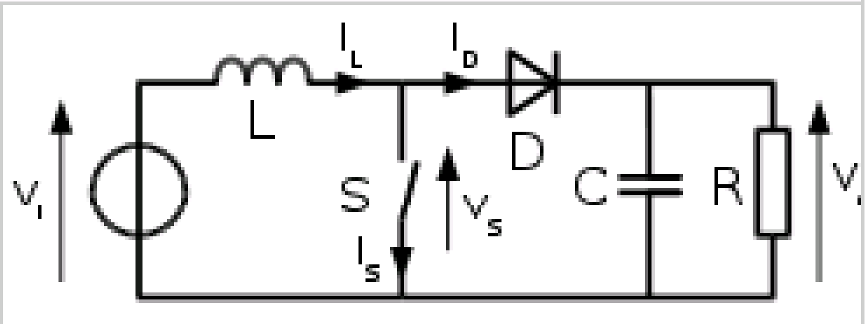


Fig. 1: Boost converter schematic

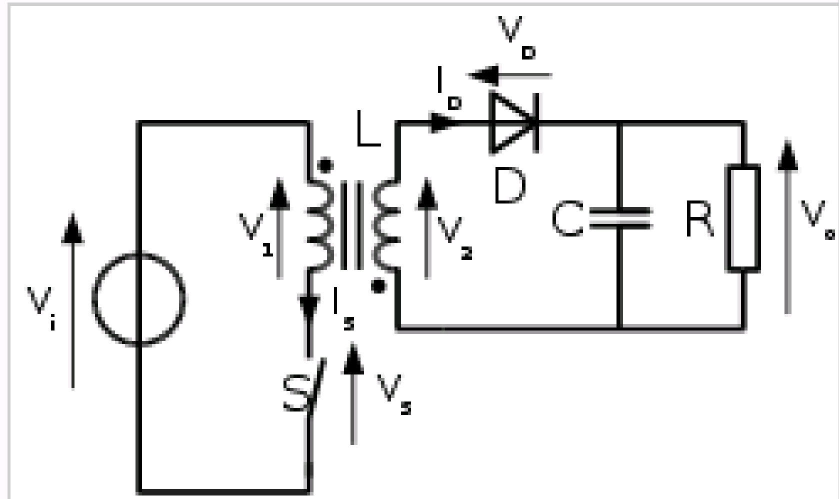
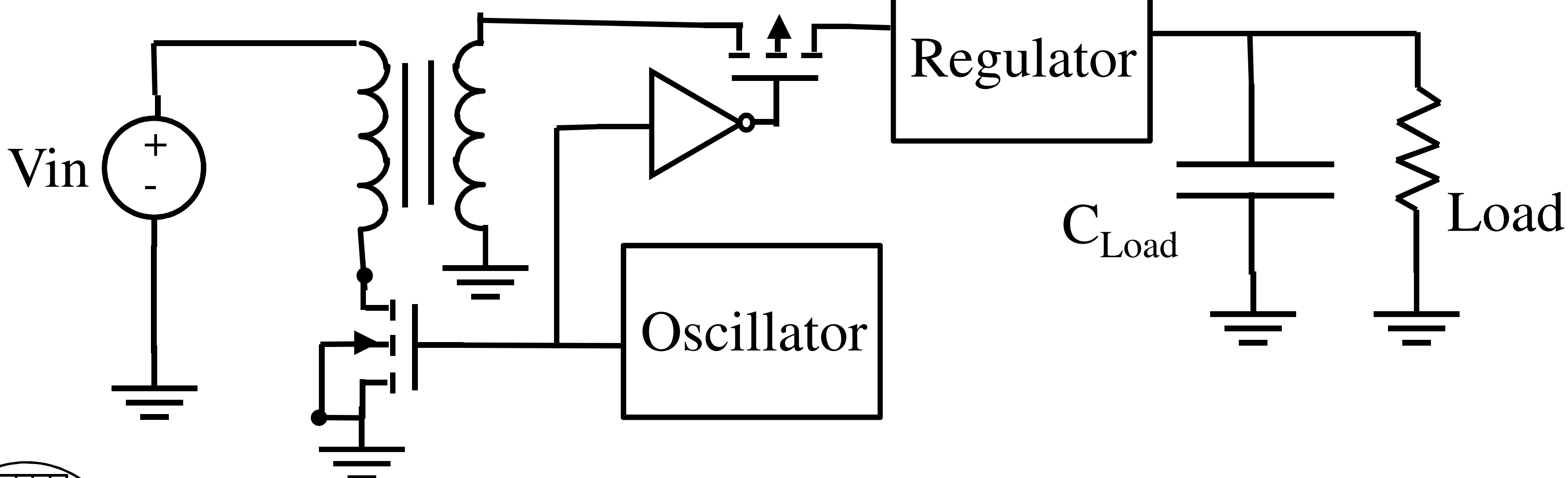


Fig. 1: Schematic of a flyback converter

ACTIVE RECTIFICATION

Active rectification is a technique where diodes are replaced by transistor switches in rectification circuits. This can improve efficiency by elimination the 0.7 volt drop across the diode and reducing the series resistance. Electronic circuits turn on the transistor switch at the appropriate time thus the name synchronous or active rectification.



Step up converter with active rectification and output voltage regulation

LINEAR TECHNOLOGY LTC3108

OPERATION

Oscillator

The LTC3108 utilizes a MOSFET switch to form a resonant step-up oscillator using an external step-up transformer and a small coupling capacitor. This allows it to boost input voltages as low as 20mV high enough to provide multiple regulated output voltages for powering other circuits. The frequency of oscillation is determined by the inductance of the transformer secondary winding and is typically in the range of 10kHz to 100kHz. For input voltages as low as 20mV, a primary-secondary turns ratio of about 1:100 is recommended. For higher input voltages, this ratio can be lower. See the Applications Information section for more information on selecting the transformer.

Charge Pump and Rectifier

The AC voltage produced on the secondary winding of the transformer is boosted and rectified using an external charge pump capacitor (from the secondary winding to pin C1) and the rectifiers internal to the LTC3108. The rectifier circuit feeds current into the VAUX pin, providing charge to the external VAUX capacitor and the other outputs.

VAUX

The active circuits within the LTC3108 are powered from VAUX, which should be bypassed with a 1µF capacitor. Larger capacitor values are recommended when using turns ratios of 1:50 or 1:20 (refer to the Typical Application examples). Once VAUX exceeds 2.5V, the main V_{OUT} is allowed to start charging.

An internal shunt regulator limits the maximum voltage on VAUX to 5.25V typical. It shunts to GND any excess current into VAUX when there is no load on the converter or the input source is generating more power than is required by the load.

LINEAR TECHNOLOGY LTC3108

Synchronous Rectifiers

Once VAUX exceeds 2V, synchronous rectifiers in parallel with each of the internal diodes take over the job of rectifying the input voltage, improving efficiency.

Low Dropout Linear Regulator (LDO)

The LTC3108 includes a low current LDO to provide a regulated 2.2V output for powering low power processors or other low power ICs. The LDO is powered by the higher of VAUX or V_{OUT}. This enables it to become active as soon as VAUX has charged to 2.3V, while the V_{OUT} storage capacitor is still charging. In the event of a step load on the LDO output, current can come from the main V_{OUT} capacitor if VAUX drops below V_{OUT}. The LDO requires a 2.2µF ceramic capacitor for stability. Larger capacitor values can be used without limitation, but will increase the time it takes for all the outputs to charge up. The LDO output is current limited to 4mA minimum.

V_{OUT}

The main output voltage on V_{OUT} is charged from the VAUX supply, and is user programmed to one of four regulated voltages using the voltage select pins VS1 and VS2, according to Table 2. Although the logic threshold voltage for VS1 and VS2 is 0.85V typical, it is recommended that they be tied to ground or VAUX.

Table 2. Regulated Voltage Using Pins VS1 and VS2

VS2	VS1	V_{OUT}
GND	GND	2.35V
GND	VAUX	3.3V
VAUX	GND	4.1V
VAUX	VAUX	5V

When the output voltage drops slightly below the regulated value, the charging current will be enabled as long as VAUX is greater than 2.5V. Once V_{OUT} has reached the proper value, the charging current is turned off.

The internal programmable resistor divider sets V_{OUT}, eliminating the need for very high value external resistors that are susceptible to board leakage.

LINEAR TECHNOLOGY LTC3108

In a typical application, a storage capacitor (typically a few hundred microfarads) is connected to V_{OUT}. As soon as VAUX exceeds 2.5V, the V_{OUT} capacitor will be allowed to charge up to its regulated voltage. The current available to charge the capacitor will depend on the input voltage and transformer turns ratio, but is limited to about 4.5mA typical.

PGOOD

A power good comparator monitors the V_{OUT} voltage. The PGD pin is an open-drain output with a weak pull-up (1MΩ) to the LDO voltage. Once V_{OUT} has charged to within 7.5% of its regulated voltage, the PGD output will go high. If V_{OUT} drops more than 9% from its regulated voltage, PGD will go low. The PGD output is designed to drive a microprocessor or other chip I/O and is not intended to drive a higher current load such as an LED. Pulling PGD up externally to a voltage greater than VLDO will cause a small current to be sourced into VLDO. PGD can be pulled low in a wire-OR configuration with other circuitry.

V_{OUT2}

V_{OUT2} is an output that can be turned on and off by the host, using the V_{OUT2_EN} pin. When enabled, V_{OUT2} is connected to V_{OUT} through a 1.3Ω P-channel MOSFET switch. This output, controlled by a host processor, can be used to power external circuits such as sensors and amplifiers, that do not have a low power sleep or shutdown capability. V_{OUT2} can be used to power these circuits only when they are needed.

Minimizing the amount of decoupling capacitance on V_{OUT2} will allow it to be switched on and off faster, allowing shorter burst times and, therefore, smaller duty cycles in pulsed applications such as a wireless sensor/transmitter. A small V_{OUT2} capacitor will also minimize the energy that will be wasted in charging the capacitor every time V_{OUT2} is enabled.

V_{OUT2} has a soft-start time of about 5µs to limit capacitor charging current and minimize glitching of the main output when V_{OUT2} is enabled. It also has a current limiting circuit that limits the peak current to 0.3A typical.

LINEAR TECHNOLOGY LTC3108

The V_{OUT2} enable input has a typical threshold of 1V with 100mV of hysteresis, making it logic-compatible. If V_{OUT2_EN} (which has an internal pull-down resistor) is low, V_{OUT2} will be off. Driving V_{OUT2_EN} high will turn on the V_{OUT2} output.

Note that while V_{OUT2_EN} is high, the current limiting circuitry for V_{OUT2} draws an extra 8μA of quiescent current from V_{OUT}. This added current draw has a negligible effect on the application and capacitor sizing, since the load on the V_{OUT2} output, when enabled, is likely to be orders of magnitude higher than 8μA.

Short-Circuit Protection

All outputs of the LTC3108 are current limited to protect against short-circuits to ground.

Output Voltage Sequencing

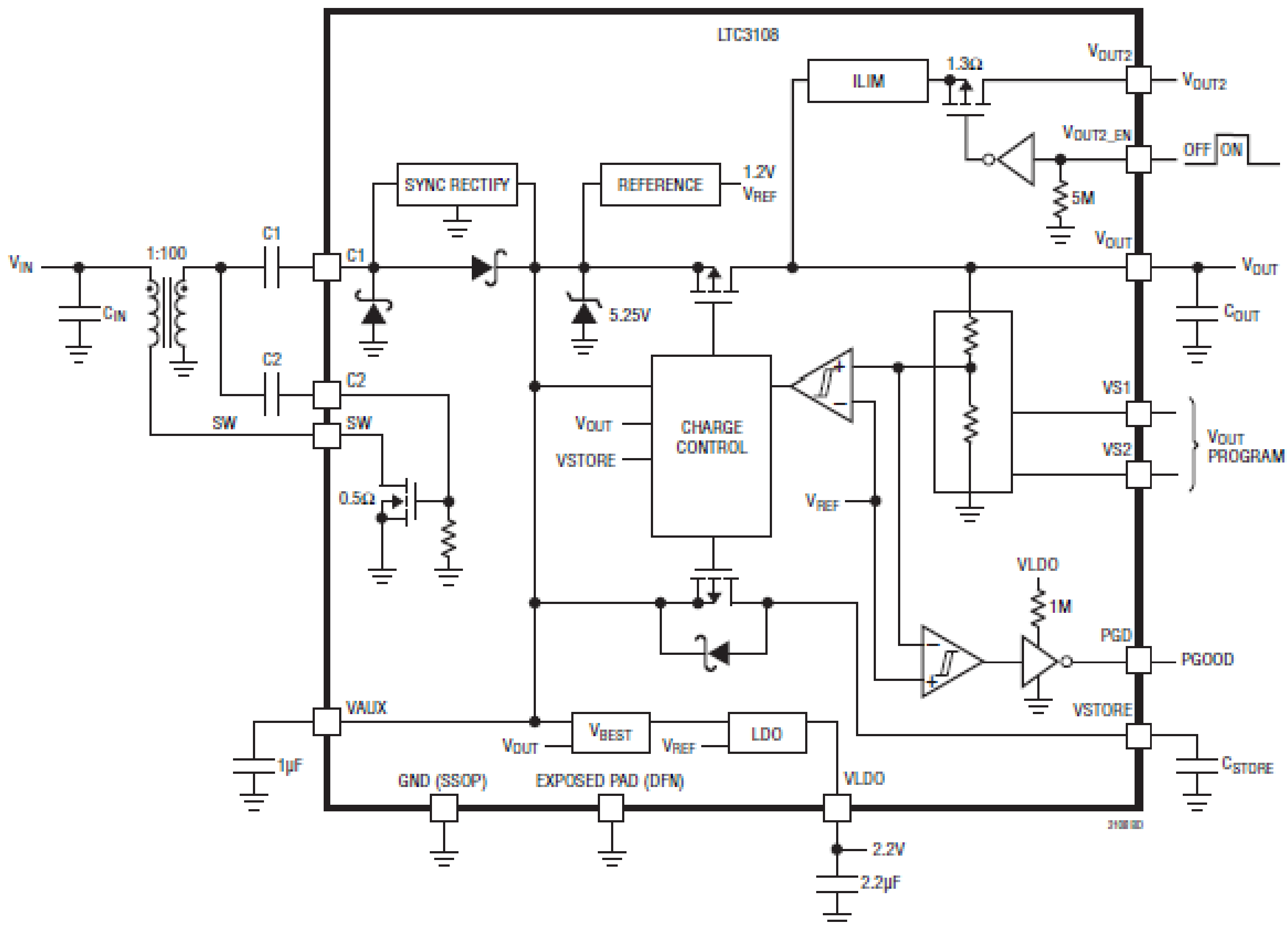
A timing diagram showing the typical charging and voltage sequencing of the outputs is shown in Figure 1. Note: time not to scale.

VSTORE

The VSTORE output can be used to charge a large storage capacitor or rechargeable battery after V_{OUT} has reached regulation. Once V_{OUT} has reached regulation, the VSTORE output will be allowed to charge up to the VAUX voltage. The storage element on VSTORE can be used to power the system in the event that the input source is lost, or is unable to provide the current demanded by the V_{OUT}, V_{OUT2} and LDO outputs. If VAUX drops below VSTORE, the LTC3108 will automatically draw current from the storage element. Note that it may take a long time to charge a large capacitor, depending on the input energy available and the loading on V_{OUT} and VLDO.

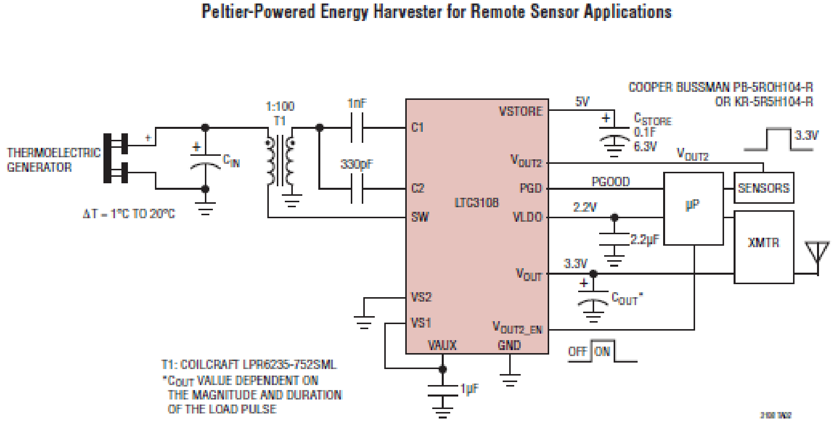
Since the maximum current from VSTORE is limited to a few milliamps, it can safely be used to trickle-charge NiCd or NiMH rechargeable batteries for energy storage when the input voltage is lost. Note that the VSTORE capacitor cannot supply large pulse currents to V_{OUT}. Any pulse load on V_{OUT} must be handled by the V_{OUT} capacitor.

LINER TECHNOLOGY ENERGY HARVESTING LTC3108

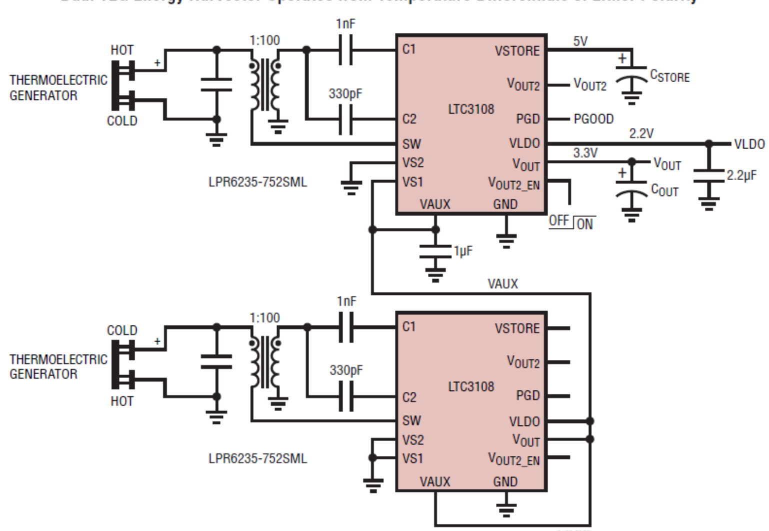


APPLICATIONS OF LTC3108 ULTRA LOW VOLTAGE STEP UP CONVERTER AND POWER MANAGER

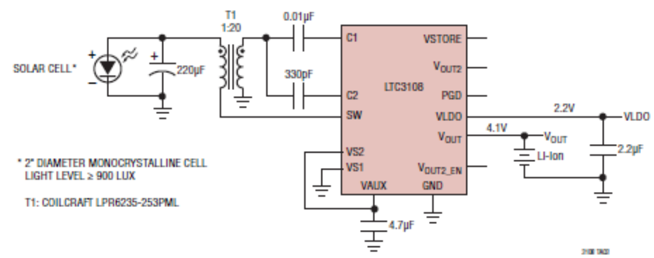
Peltier-Powered Energy Harvester for Remote Sensor Applications



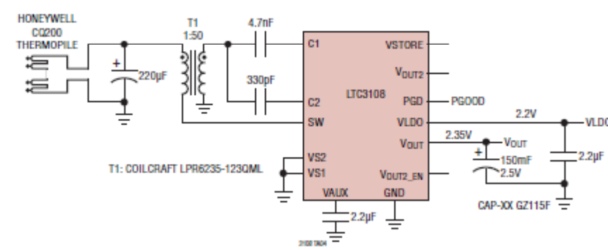
Dual TEG Energy Harvester Operates from Temperature Differentials of Either Polarity



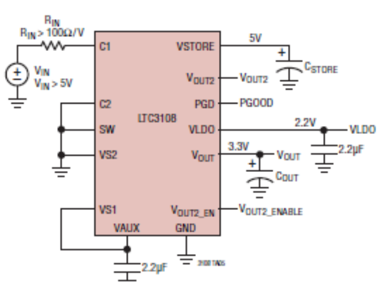
Li-Ion Battery Charger and LDO Powered by a Solar Cell



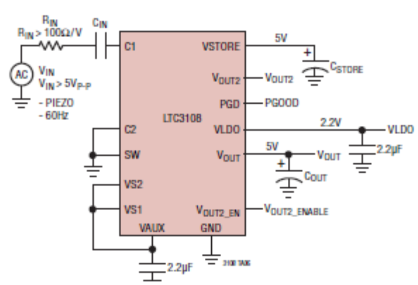
Supercapacitor Charger and LDO Powered by a Thermopile Generator



DC Input Energy Harvester and Power Manager



AC Input Energy Harvester and Power Manager



ULTRA-LOW POWER MICROCONTROLLERS

16 Bit, RISC,
Low supply Voltage 1.8 to 3.6V
Ultra-Low Power Consumption

Active Mode	220 uA
Standby Mode	0.5uA
Off Mode	0.1uA

Five Power Saving Modes
1Mhz, 100Khz, 4Khz

mode 0 Active	85uA
mode 2	22uA
mode 3	1uA
mode 4	0.5uA

Analog Input 0 to Vcc
Cost ~$1

13.6K < Rload < 6MEG ohm

TEXAS INSTRUMENTS

MSP430F20x3
MSP430F20x2
MSP430F20x1

www.ti.com SLAS491H – AUGUST 2005 – REVISED AUGUST 2011

MIXED SIGNAL MICROCONTROLLER

FEATURES

- Low Supply Voltage Range 1.8 V to 3.6 V
- Ultra-Low Power Consumption
  - Active Mode: 220 µA at 1 MHz, 2.2 V
  - Standby Mode: 0.5 µA
  - Off Mode (RAM Retention): 0.1 µA
- Five Power-Saving Modes
- Ultra-Fast Wake-Up From Standby Mode in Less Than 1 µs
- 16-Bit RISC Architecture, 62.5-ns Instruction Cycle Time
- Basic Clock Module Configurations:
  - Internal Frequencies up to 16 MHz With Four Calibrated Frequencies to ±1%
  - Internal Very Low-Power Low-Frequency Oscillator
  - 32-kHz Crystal
  - External Digital Clock Source
- 16-Bit Timer_A With Two Capture/Compare Registers
- On-Chip Comparator for Analog Signal Compare Function or Slope A/D (MSP430F20x1)
- 10-Bit 200-ksps A/D Converter With Internal Reference, Sample-and-Hold, and Autoscan (MSP430F20x2)
- 16-Bit Sigma-Delta A/D Converter With Differential PGA Inputs and Internal Reference (MSP430F20x3)
- Universal Serial Interface (USI) Supporting SPI and I2C (MSP430F20x2 and MSP430F20x3)
- Brownout Detector
- Serial Onboard Programming, No External Programming Voltage Needed, Programmable Code Protection by Security Fuse
- On-Chip Emulation Logic With Spy-Bi-Wire Interface
- Family Members:
  - MSP430F2001
    - 1KB + 256B Flash Memory
    - 128B RAM
  - MSP430F2011
    - 2KB + 256B Flash Memory
    - 128B RAM
  - MSP430F2002
    - 1KB + 256B Flash Memory
    - 128B RAM
  - MSP430F2012
    - 2KB + 256B Flash Memory
    - 128B RAM
  - MSP430F2003
    - 1KB + 256B Flash Memory
    - 128B RAM
  - MSP430F2013
    - 2KB + 256B Flash Memory
    - 128B RAM
- Available in 14-Pin Plastic Small-Outline Thin Package (TSSOP), 14-Pin Plastic Dual Inline Package (PDIP), and 16-Pin QFN
- For Complete Module Descriptions, See the *MSP430x2xx Family User's Guide* (SLAU144)

DESCRIPTION

The Texas Instruments MSP430 family of ultra-low-power microcontrollers consist of several devices featuring different sets of peripherals targeted for various applications. The architecture, combined with five low-power modes is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows wake-up from low-power modes to active mode in less than 1 µs.

The MSP430F20xx series is an ultra-low-power mixed signal microcontroller with a built-in 16-bit timer and ten I/O pins. In addition, the MSP430F20x1 has a versatile analog comparator. The MSP430F20x2 and MSP430F20x3 have built-in communication capability using synchronous protocols (SPI or I2C) and a 10-bit A/D converter (MSP430F20x2) or a 16-bit sigma-delta A/D converter (MSP430F20x3).

LMV551/552/554 MICRO POWER OP AMP

National Semiconductor

October 8, 2008

LMV551/LMV552/LMV554
3 MHz, Micropower RRO Amplifiers

General Description

The LMV551/LMV552/LMV554 are high performance, low power operational amplifiers implemented with National's advanced VIP50 process. They feature 3 MHz of bandwidth while consuming only 37 µA of current per amplifier, which is an exceptional bandwidth to power ratio in this op amp class. These amplifiers are unity gain stable and provide an excellent solution for low power applications requiring a wide bandwidth.

The LMV551/LMV552/LMV554 have a rail-to-rail output stage and an input common mode range that extends below ground.

The LMV551/LMV552/LMV554 have an operating supply voltage range from 2.7V to 5.5V. These amplifiers can operate over a wide temperature range (–40°C to 125°C) making them a great choice for automotive applications, sensor applications as well as portable instrumentation applications. The LMV551 is offered in the ultra tiny 5-Pin SC70 and 5-Pin SOT-23 package. The LMV552 is offered in an 8-Pin MSOP package. The LMV554 is offered in the 14-Pin TSSOP.

Features

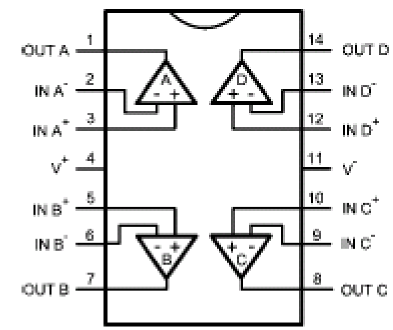
(Typical 5V supply, unless otherwise noted.)

- Guaranteed 3V and 5.0V performance
- High unity gain bandwidth — 3 MHz
- Supply current (per amplifier) — 37 µA
- CMRR — 93 dB
- PSRR — 90 dB
- Slew rate — 1 V/µs
- Output swing with 100 kΩ load — 70 mV from rail
- Total harmonic distortion — 0.003% @ 1 kHz, 2 kΩ
- Temperature range — –40°C to 125°C

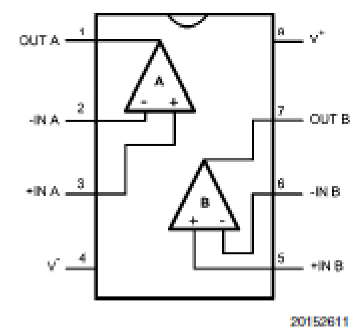
Applications

- Active filter
- Portable equipment
- Automotive
- Battery powered systems
- Sensors and Instrumentation

14-Pin TSSOP

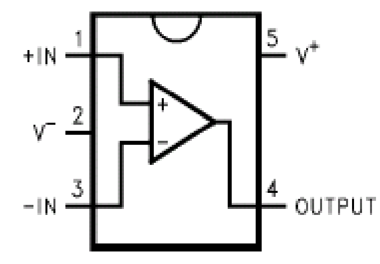


8-Pin MSOP



Top View

5-Pin SC70/ SOT-23



0.6 uA OP AMP

Touchstone SEMICONDUCTOR

TS1001

THE ONLY 0.8V/0.6µA RAIL-TO-RAIL OP AMP

FEATURES

Single 0.65V to 2.5V Operation
Supply current: 0.6µA (typ)
Offset voltage: 0.5mV (typ)
Low TCV_{OS}: 20µV/°C (typ)
A_{VOL} Driving 100kΩ Load: 90dB (min)
Unity Gain Stable
Rail-to-rail Input and Output
No Output Phase Reversal
5-pin SC70 Package

APPLICATIONS

Battery/Solar-Powered Instrumentation
Portable Gas Monitors
Low-voltage Signal Processing
Nanopower Active Filters
Wireless Remote Sensors
Battery-powered Industrial Sensors
Active RFID Readers
Powerline or Battery Current Sensing
Handheld/Portable POS Terminals

DESCRIPTION

The TS1001 is the industry's first sub-1µA supply current, precision CMOS operational amplifier rated to operate at a nominal supply voltage of 0.8V. Optimized for ultra-long-life battery-powered applications, the TS1001 is Touchstone's first operational amplifier in the "NanoWatt Analog™" high-performance analog integrated circuits portfolio. The TS1001 exhibits a typical input offset voltage of 0.5mV, a typical input bias current of 25pA, and rail-to-rail input and output stages. The TS1001 can operate from single-supply voltages from 0.65V to 2.5V.

The TS1001's combined features make it an excellent choice in applications where very low supply current and low operating supply voltage translate into very long equipment operating time. Applications include: nanopower active filters, wireless remote sensors, battery and powerline current sensors, portable gas monitors, and handheld/portable POS terminals.

The TS1001 is fully specified at V_{DD} = 0.8V and over the industrial temperature range (−40°C to +85°C) and is available in a PCB-space saving 5-lead SC70 surface-mount package.

BATTERIES

Arduino-BT running blink and serial port write every second uses 20 mA at 3volts or 60 mW

AA Battery Stores ~2000 mAh of Charge Q
Time = Q / I = 2000 / 20 = 100 hours

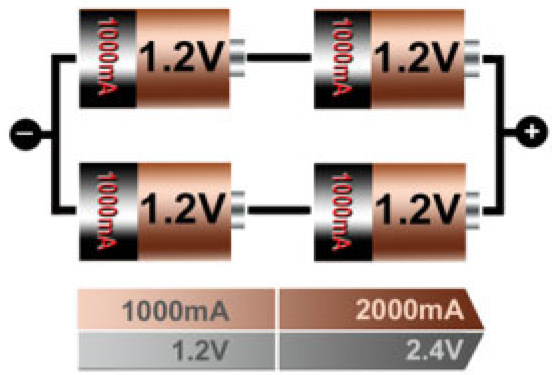
CR2032 Battery Stores ~200 mAh of Charge Q
Time = 200/20 = 10 hours

1 month is 720 hours
Current = Q / time
I = 2.8 mA

Battery Type	Capacity (mAh)
D	12000
C	6000
AA	2000
AAA	1000
N	650
9 Volt	500
6 Volt Lantern	11000

BATTERIES

Batteries in series doubles the voltage but maintains the same capacity
Batteries in parallel doubles the capacity but maintains the same voltage



Four AA connected batteries as shown give 4000mAh at 2.4V

2000 mAh, at 1.2V

Rochester Institute of Technology
Microelectronic Engineering

BATTERY LIFE CALCULATIONS

:MCR 688 MEMS Evaluation			**Dr. Lynn Fuller**
'ower Calculations for Energy Harvesting			**11/6/2012**
Inputs			
;upply Voltage	V =	3	volts
/licrocontroller Active Mode	I1 =	220	uA
/licrocontroller Standby Mode	I2 =	1	uA
/licrocontroller Transmit Mode	I3 =	10	mA
'ercent of time Active	% Active =	3.5	%
'ercent of time Standby	% Standby =	96	%
'ercent of time Transmit	% Transmit =	0.5	%
;attery Capacity	Q =	200	mA- Hours
Calculations			
'otal of Percentages		100	Should be equal to 100%
Average Current Used	I Ave =	59	uA
'ime System can run on Batteries	T =	3409	hours
	T =	142	days
	T =	5	months
	Transmit Time =	18.00	seconds per hour
	Transmit Period =	3.33	minutes (if Transmission is 1 second duration)
	Transmit Rate =	0.30	Times/min (if Transmission is 1 second duration)

T = Q / IAve

STORAGE USING SUPER CAPACITOR OR BATTERY

All prices are in US dollars.

Digi-Key Part Number	P6980-ND
Quantity Available	8,522
Manufacturer	Panasonic - ECG
Manufacturer Part Number	EEC-S5R5H474
Description	CAP SUPER 470MF 5.5V RADIAL
Lead Free Status / RoHS Status	Lead free / RoHS Compliant

Price Break	Unit Price	Extended Price
1	3.74000	3.74
50	2.59160	129.58
100	2.35050	235.05
500	1.74784	873.92
1,000	1.62729	1,627.29
5,000	1.53689	7,684.43
10,000	1.50675	15,067.50

Quantity	Item Number	Customer Reference	
	P6980-ND		Add to Order

Image shown is a representation only. Exact specifications should be obtained from the product data sheet.

Coin type, thru hole mount, 20mm Diameter, 5mm high, 0.47F, 5.5 Volt

Price $3.74 for quantity of 1, $1.63 for quantity of 1000

Q=CV = 0.47F 5.5V = 2.585 Coulomb = 0.718 mAhr

compare to 2032 battery with Q=200 mAhr

100F capacitor ~ = 2032 battery

POWER – CURRENT – TIME CALCULATIONS

EMCR 688 MEMS Evaluation					**Dr. Lynn Fuller**
Power Calculations for Energy Harvesting					**5/19/2012**
Inputs					
Supply Voltage	V =	3	volts		
Microcontroller Active Mode	I1 =	220	uA		
Microcontroller Standby Mode	I2 =	1	uA		
Microcontroller Transmit Mode	I3 =	10	mA		
Percent of time Active	% Active =	3.5	%		
Percent of time Standby	% Standby =	96	%		
Percent of time Transmit	% Transmit =	0.5	%		
Energy Harvesting Current	I harvesting =	5	mA	at	0.4 Volts
Percent of Time Harvesting Available		30	%		
Storage Capacitor	Cs =	2	F		
Storage Voltage	Vst =	5	volts		
Time System has been operating	T =	24	hours		
Calculations					
Total of Percentages		100	Should be equal to 100%		
Average Power Harvested	P ave =	0.0006	Watt		
Energy Harvested	E harvested =	51.84	joules		
Energy Used in time T	E used =	15.205	joules		
Energy Stored in time T	E stored =	36.635	joules		
Useable Energy	E available =	4.000	joules		
Maximum Energy Stored	E max =	25.000	joules	Emax = $CV^2/2$	
Average Current Used	I Ave =	59	uA		
Time System can run on stored en	trs =	19	hours	trs = C (Vstore - V) / I	

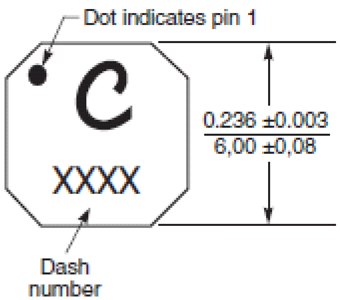
REFERENCES

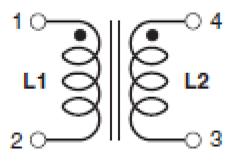
1. Giancoli, D. C. (1998). *Physics: Principles with Applications* (5th). Upper Saddle River: Prentice Hall.
2. Magnet wire. Ordered June 2008, from Bulk Wire Web site: http://www.bulkwire.com/product.asp?ProdID=7589&CtgID=6578
3. Neodynium ring magnets. Ordered June 2008, from K&J Magnetics Web site: http://www.kjmagnetics.com/products.asp?cat=16
4. Wikipedia the free encyclopedia.
5. Digikey.com
6. Linear Technology
7. Coil Craft
8. TI.com

HOMEWORK- ENERGY HARVESTING

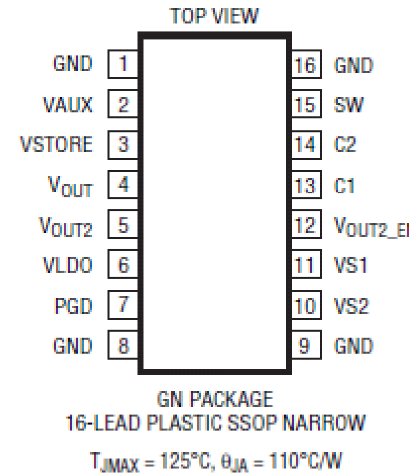
1. How can transistors be used in rectifier circuits? What is the advantage over diodes.
2. How can an inductor and switch generate a large voltage from a small DC voltage source?
3. Look up super capacitors at Digikey. Find capacitors that are rated for 5 volts. What is the largest capacitance available. What is the cost of a 5 volt 1F capacitor.
4. How long can a 1F capacitor supply a constant current of 10mA before the voltage drops from 5 to 4 volts?

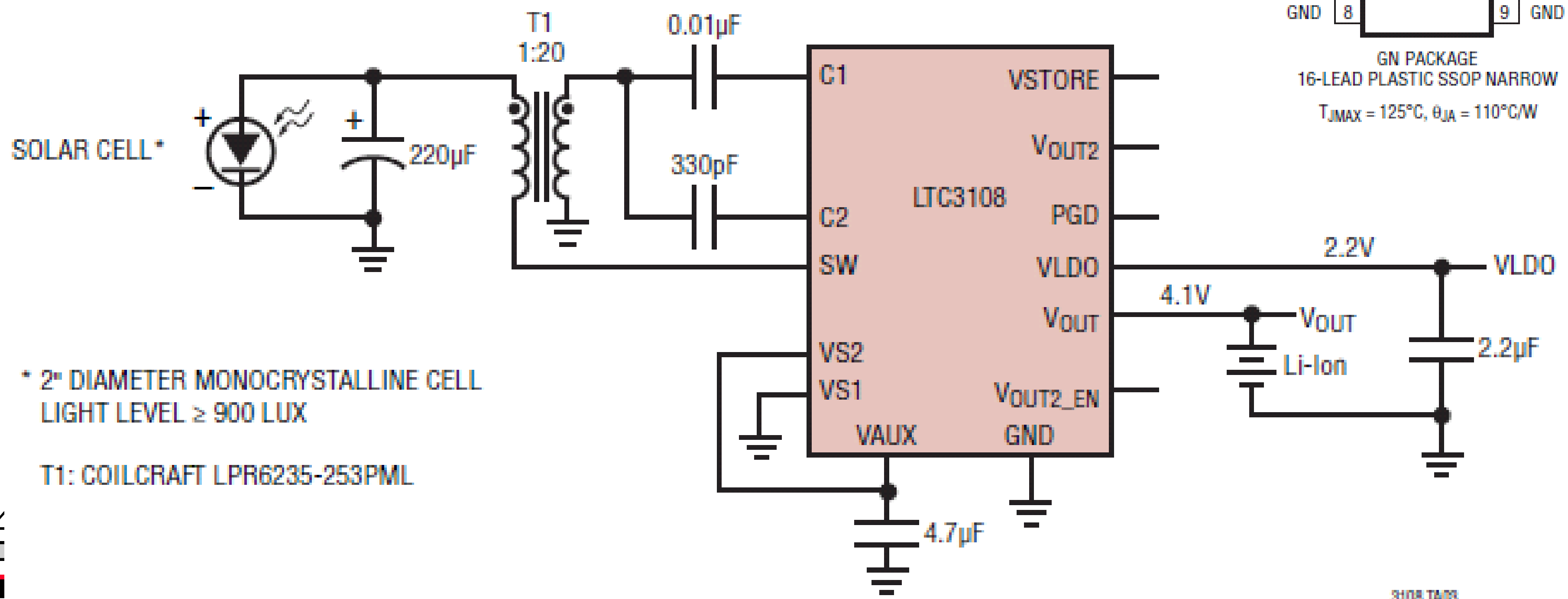
LTC3108 SOLAR CELL TO SUPER CAPACITOR





Charger and LDO Powered by a Solar Cell

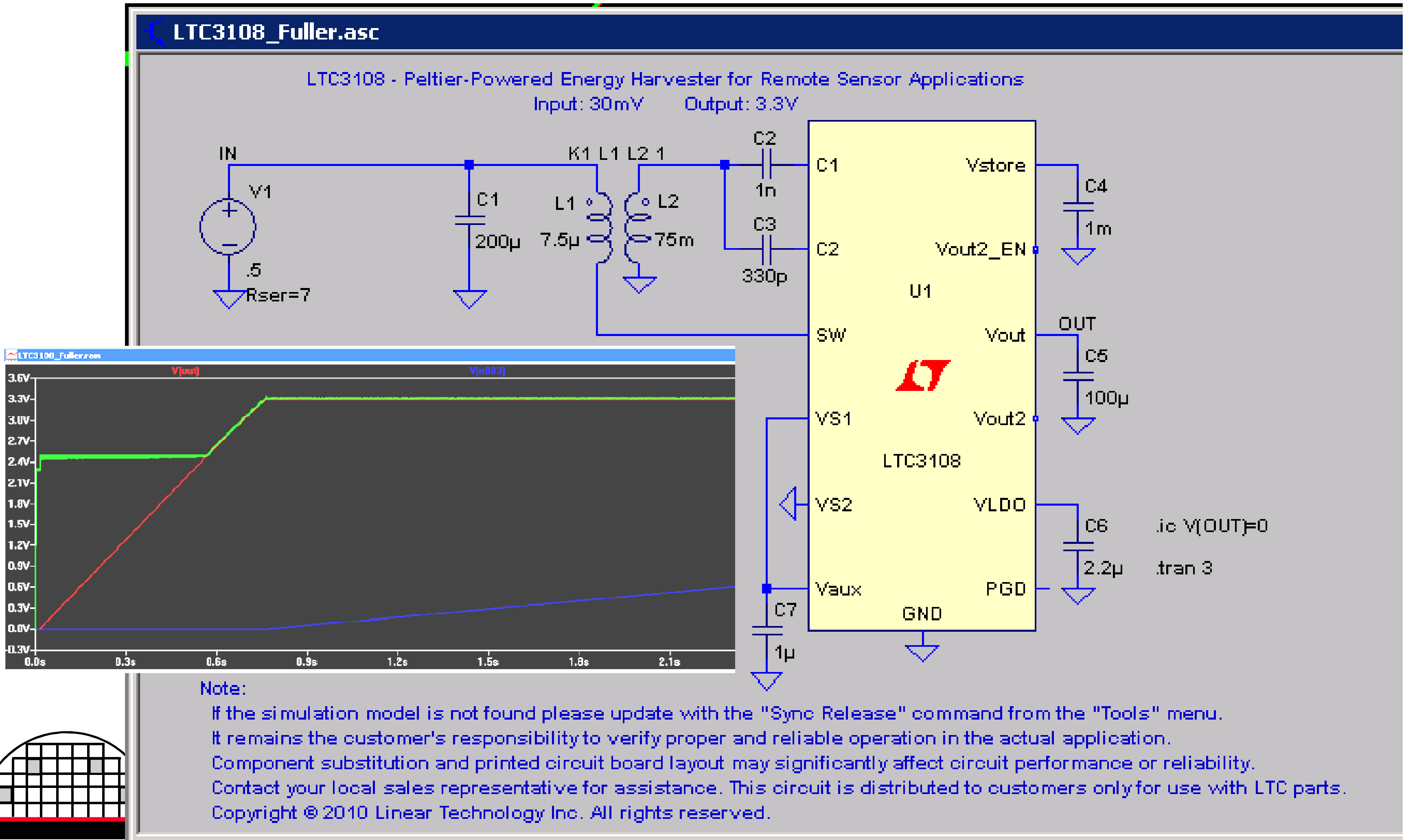




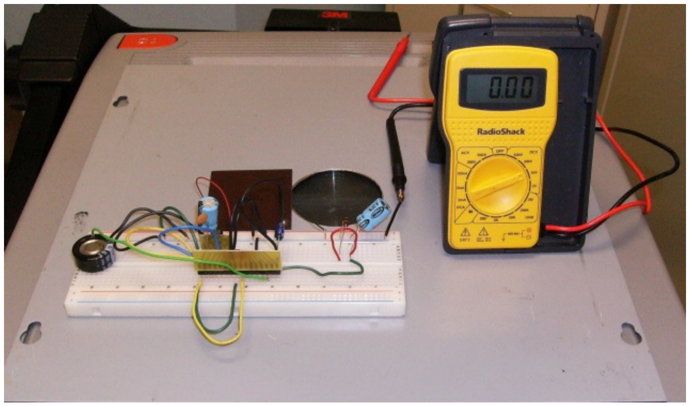
* 2" DIAMETER MONOCRYSTALLINE CELL
LIGHT LEVEL ≥ 900 LUX

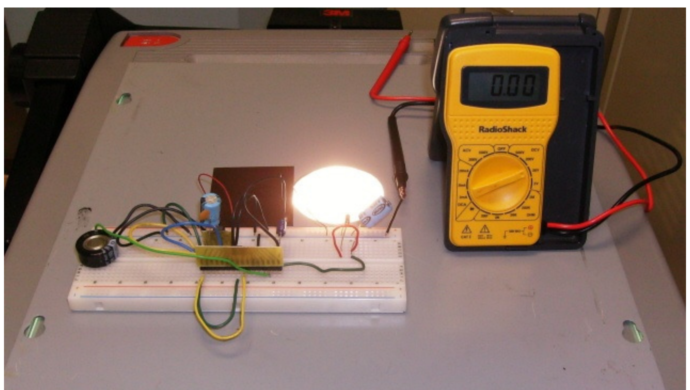
T1: COILCRAFT LPR6235-253PML

SPICE SIMULATION



BREADBOARD AND TEST SETUP





LTC3105 SOLAR CELL TO SUPER CAPACITOR

LINEAR TECHNOLOGY

LTC3105

400mA Step-Up DC/DC Converter with Maximum Power Point Control and 250mV Start-Up

FEATURES

- **Low Start-Up Voltage: 250mV**
- **Maximum Power Point Control**
- **Wide V_{IN} Range: 225mV to 5V**
- **Auxiliary 6mA LDO Regulator**
- **Burst Mode® Operation: I_Q = 24µA**
- Output Disconnect and Inrush Current Limiting
- $V_{IN} > V_{OUT}$ Operation
- Antiringing Control
- Soft Start
- Automatic Power Adjust
- Power Good Indicator
- 10-Lead 3mm × 3mm × 0.75mm DFN and 12-Lead MSOP Packages

APPLICATIONS

- Solar Powered Battery/Supercapacitor Chargers
- Energy Harvesting
- Remote Industrial Sensors
- Low Power Wireless Transmitters
- Cell Phone, MP3, PMP and GPS Accessory Chargers

DESCRIPTION

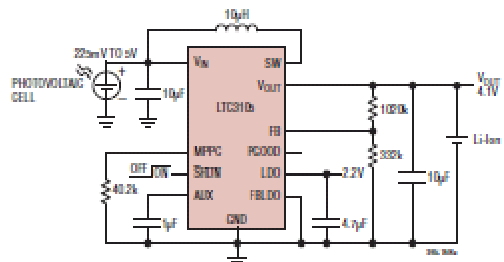
The LTC®3105 is a high efficiency step-up DC/DC converter that can operate from input voltages as low as 225mV. A 250mV start-up capability and integrated maximum power point controller (MPPC) enable operation directly from low voltage, high impedance alternative power sources such as photovoltaic cells, TEGs (thermoelectric generators) and fuel cells. A user programmable MPPC set point maximizes the energy that can be extracted from any power source. Burst Mode operation, with a proprietary self adjusting peak current, optimizes converter efficiency and output voltage ripple over all operating conditions.

The AUX powered 6mA LDO provides a regulated rail for external microcontrollers and sensors while the main output is charging. In shutdown, I_Q is reduced to 10µA and integrated thermal shutdown offers protection from overtemperature faults. The LTC3105 is offered in 10-lead 3mm × 3mm × 0.75mm DFN and 12-lead MSOP packages.

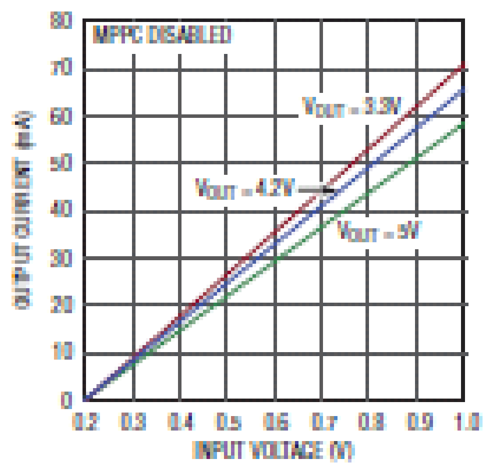
LT, LTC, LTM, Linear Technology, the Linear logo and Burst Mode are registered trademarks and ThinSOT is a trademark of Linear Technology Corporation. All other trademarks are the property of their respective owners.

TYPICAL APPLICATION

Single Photovoltaic Cell Li-Ion Trickle Charger



Output Current vs Input Voltage



IXOLAR SOLAR CELL – MEASURED CHARACTERISTICS

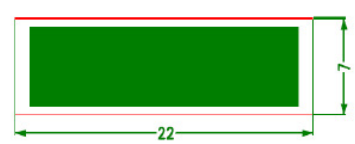
MEASURED I_{SC}	Cell 1	Cell2	Measured Light Intensity
Room Light at Desk Top	0.0705mA	0.0509mA	300 Lux
Close to Light Fixture	1.574mA	1.560mA	XXX Lux
Highest Microscope Illuminator Setting	51.2mA	48.6mA	XXX Lux
Overhead Projector	13.6mA	15mA	XX Lux (~2.5mW/cm^2)
Direct Sunlight Through Window	16.0mA	16.0mA	65,000 Lux
Dark Current	58.1nA	17.8nA	zero
Series Resistance	1.6966Ω	1.5363Ω	
Parallel Resistance	>1MEG	>1MEG	

(~25w/m^2 = ~2.5mW/cm^2)

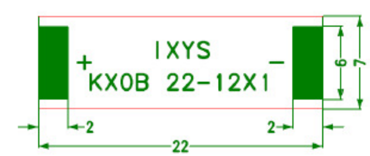
Package front-side and back-side view.

IXOLAR – KXOB22-12X1

SolarBIT Pad Design. (Dimensions in millimeters)



Front-side View details



Back-side View details

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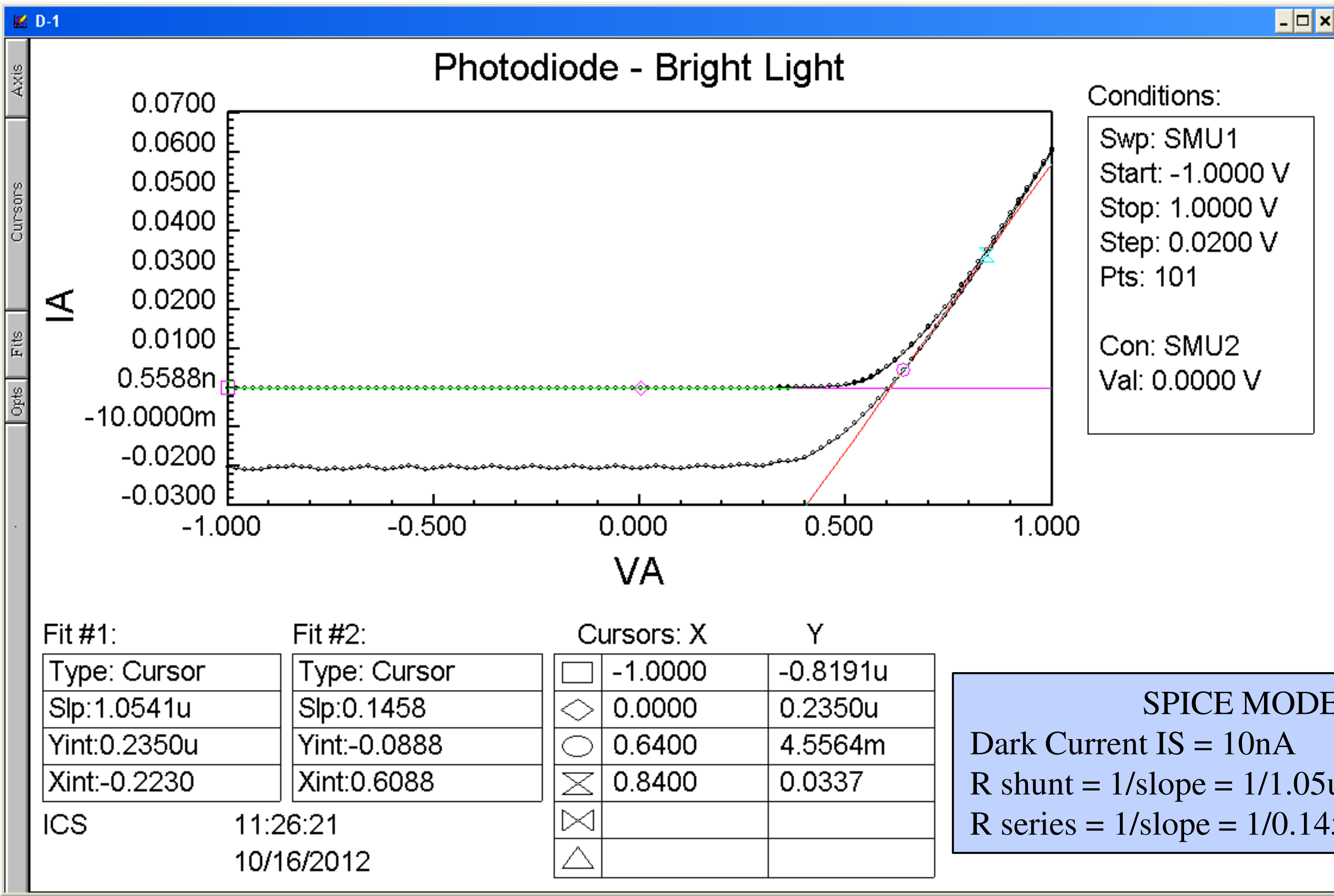
Microelectronic Engineering

EXTRACT SPICE MODEL FROM I-V CHARACTERISTICS



SPICE MODEL

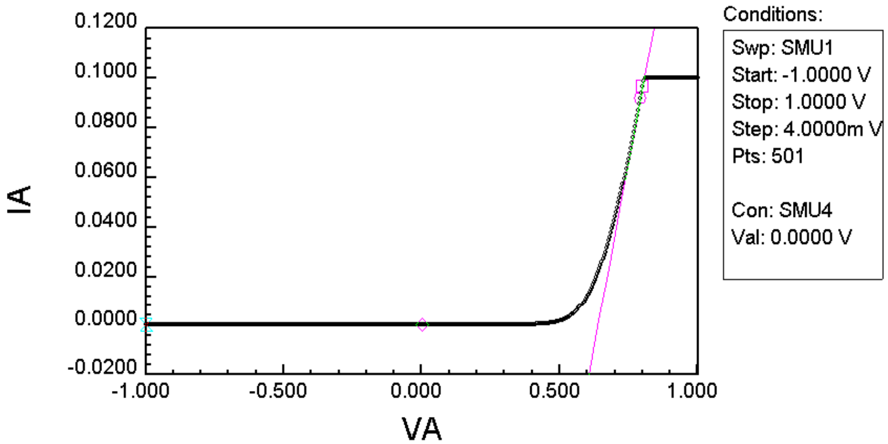
Dark Current IS = 10nA

R shunt = 1/slope = 1/1.05u = ~1 MEG ohm

R series = 1/slope = 1/0.1458 = 6.86 ohm

MEASURED 7MMX22MM SOLAR CELL

Solar Cell (1) - Dark Current

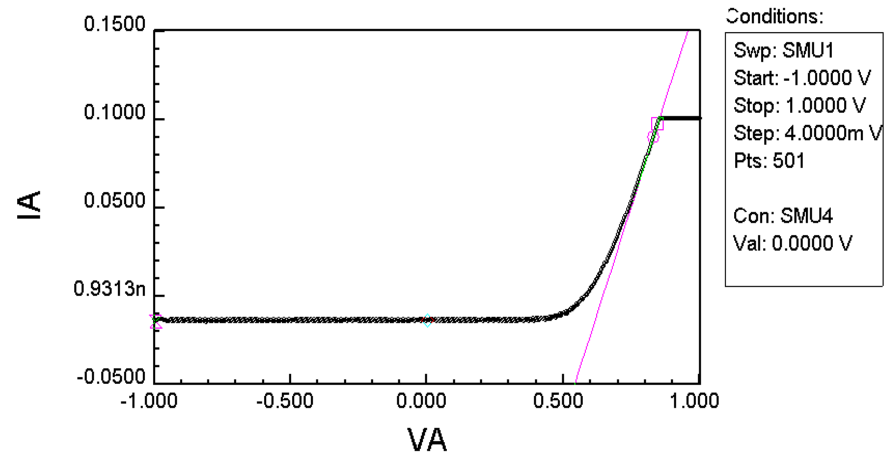


Fit #1:	Fit #2:
Type: Linear	None
Slp:0.5894	****
Y-int:-0.3752	****
X-int:0.6366	***

Cursors:	X	Y
□	0.8000	0.0963
◇	0.0000	0.0581u
○	0.7920	0.0916
⌛	-1.0000	-0.1355m
⋈		
△		

ICS 14:02:07 01/23/2013

Solar Cell (1) – Bright light, Overhead projector

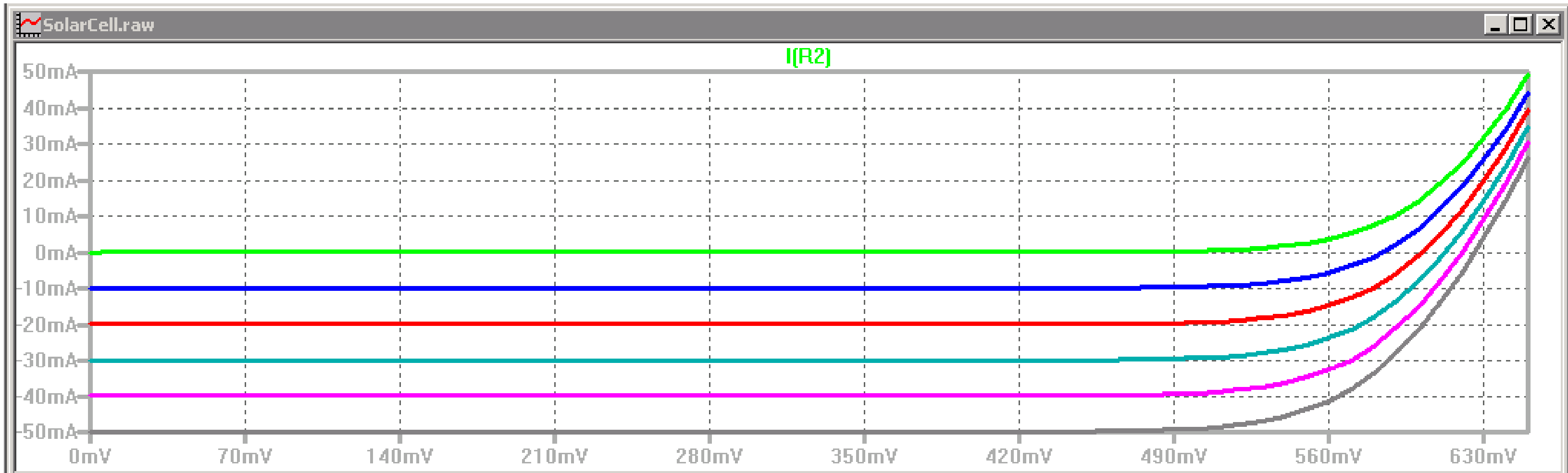


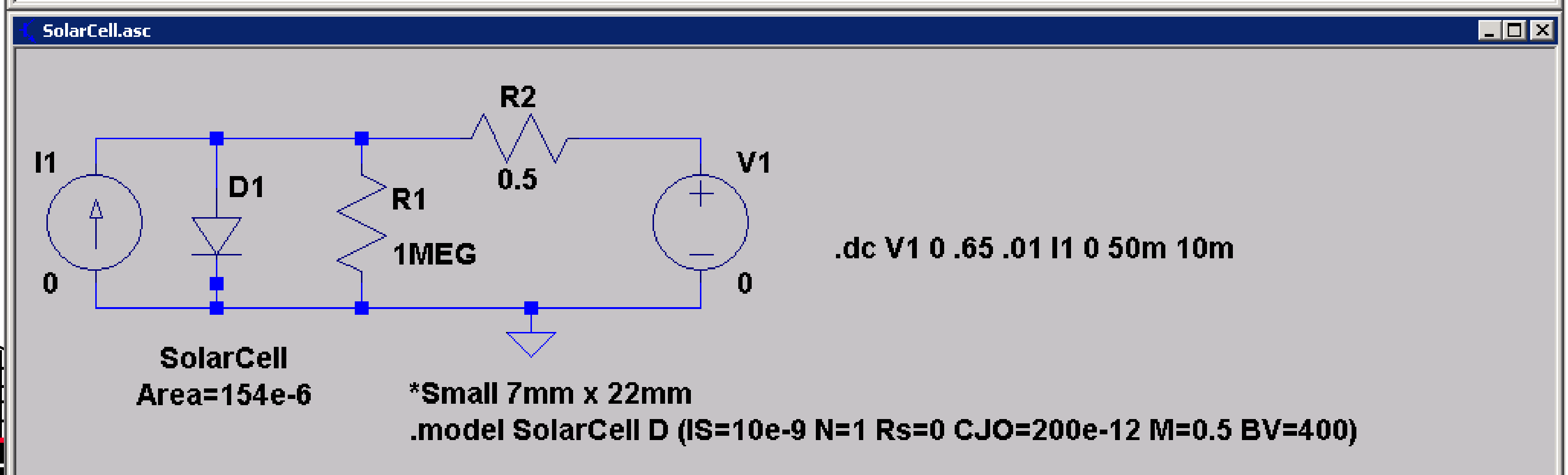
Fit #1:	Fit #2:
Type: Linear	None
Slp:0.4826	****
Y-int:-0.3102	****
X-int:0.6429	***

Cursors:	X	Y
□	0.8440	0.0971
◇	0.0000	-0.0136
○	0.8280	0.0893
⌛	-0.9960	-0.0148
⋈		
△		

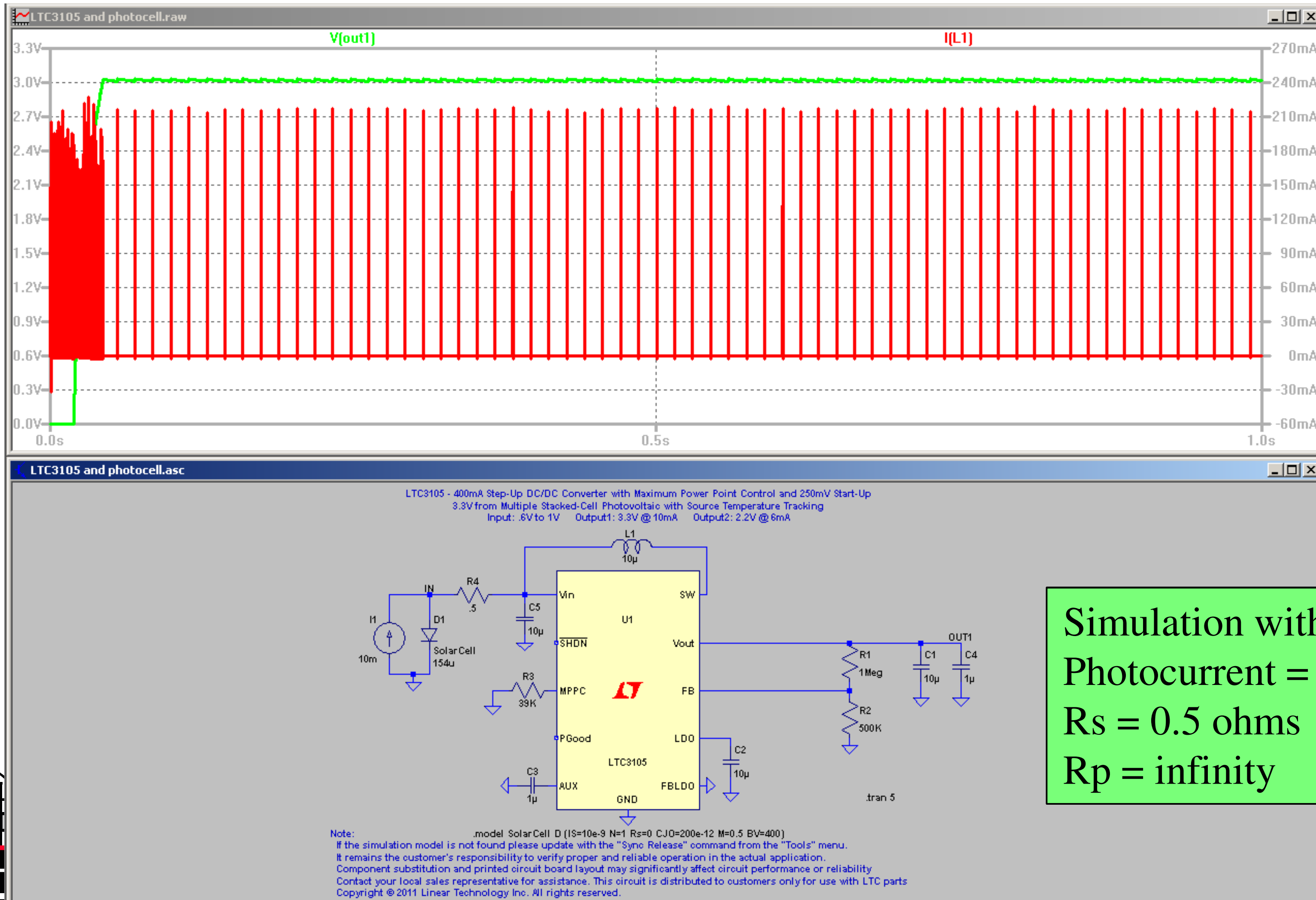
ICS 12:55:25 01/23/2013

LTSPICE SIMULATION OF 7MMX22MM SOLAR CELL



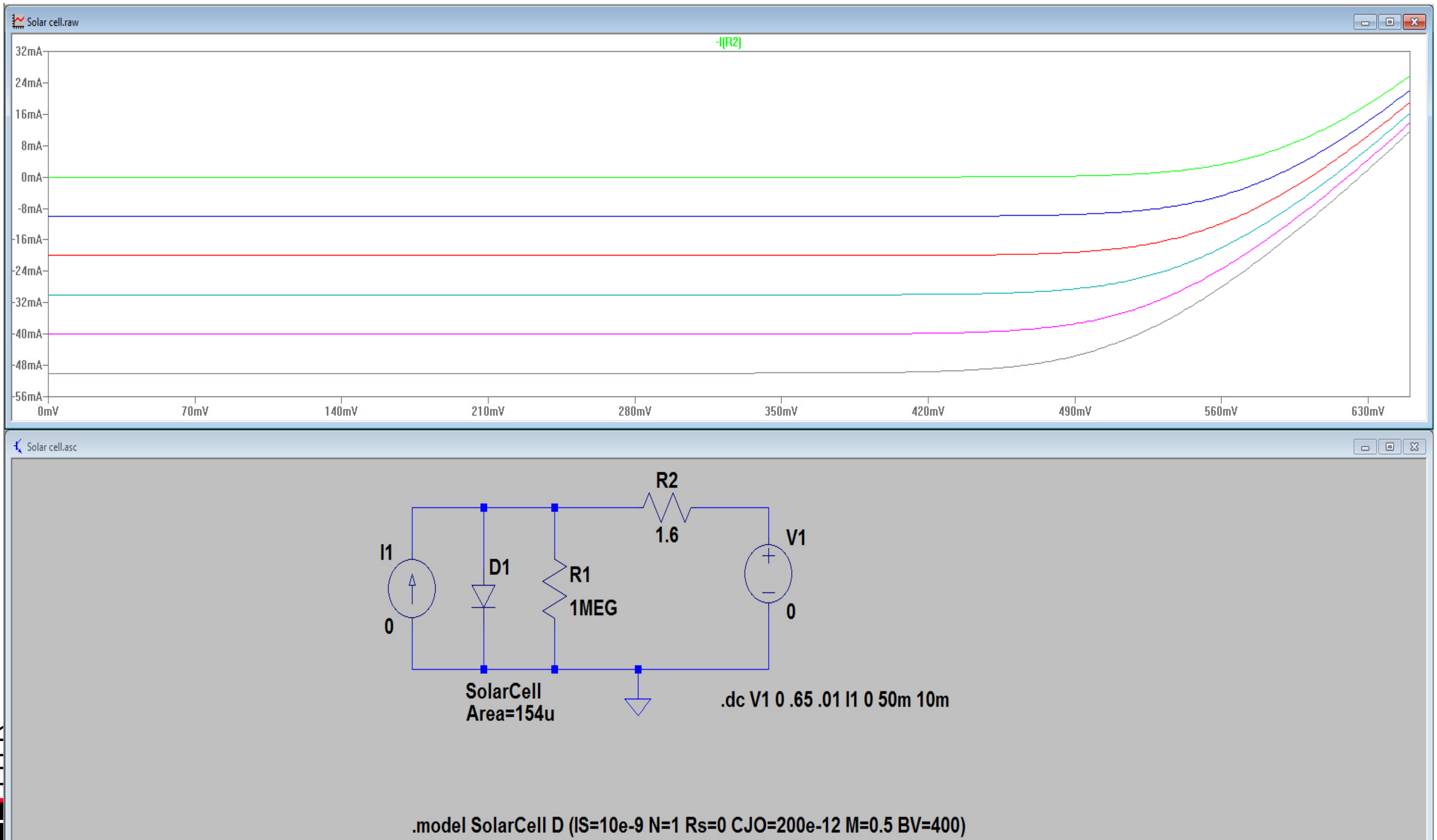


OUTPUT VOLTAGE AND INDUCTOR CURRENT

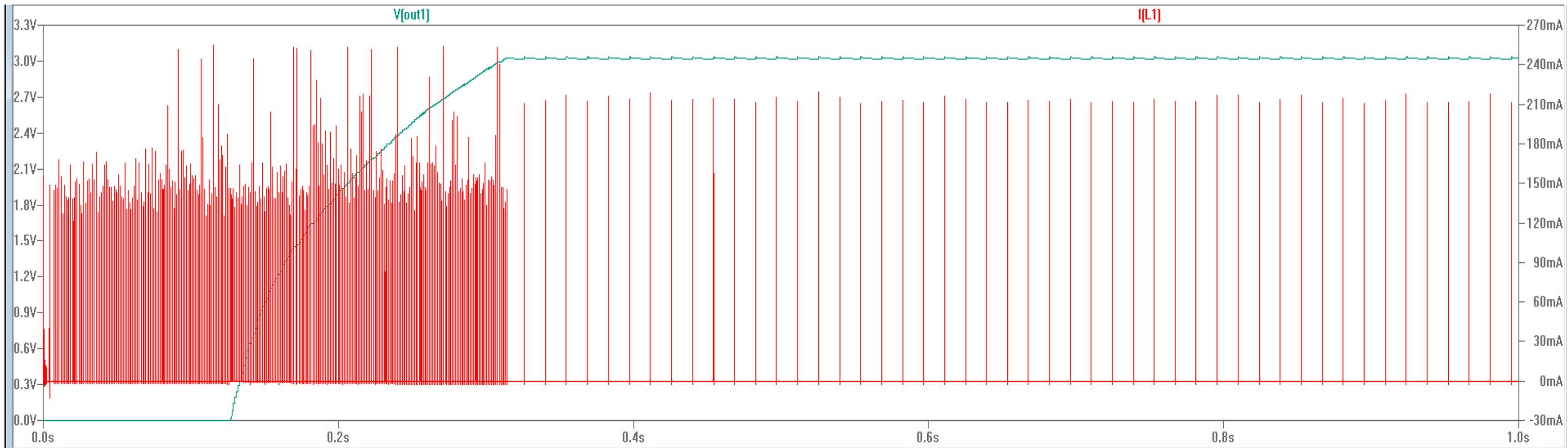


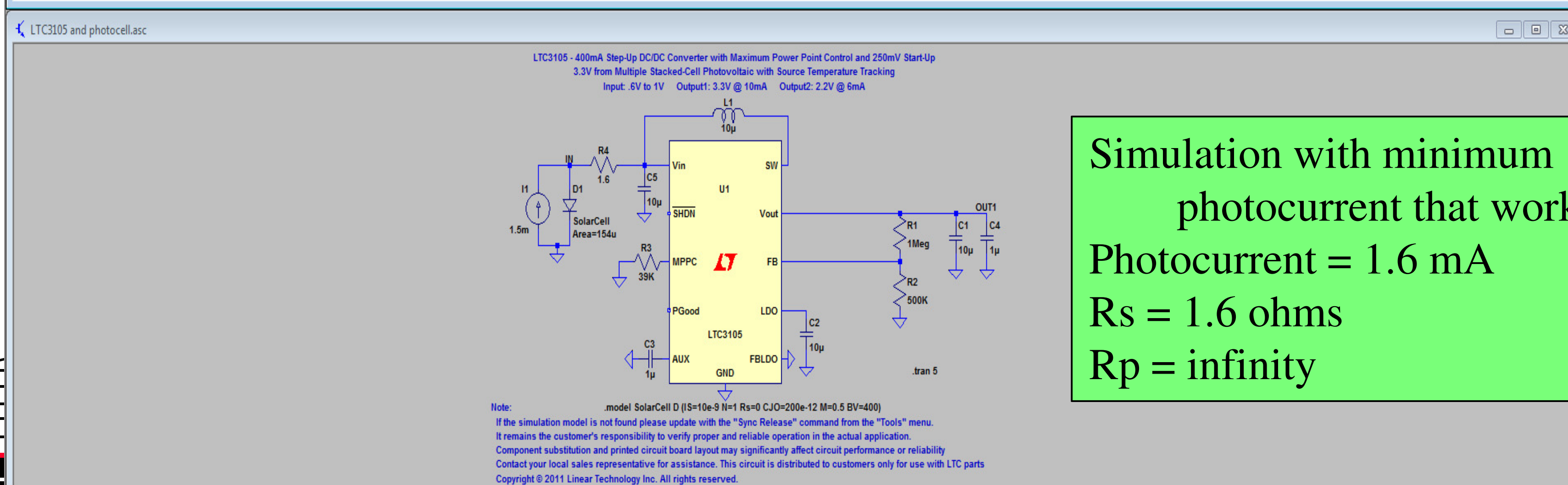
Simulation with
Photocurrent = 10mA
Rs = 0.5 ohms
Rp = infinity

LTSPICE SIMULATION OF 7MMX22MM SOLAR CELL



OUTPUT VOLTAGE AND INDUCTOR CURRENT





Simulation with minimum photocurrent that works

Photocurrent = 1.6 mA

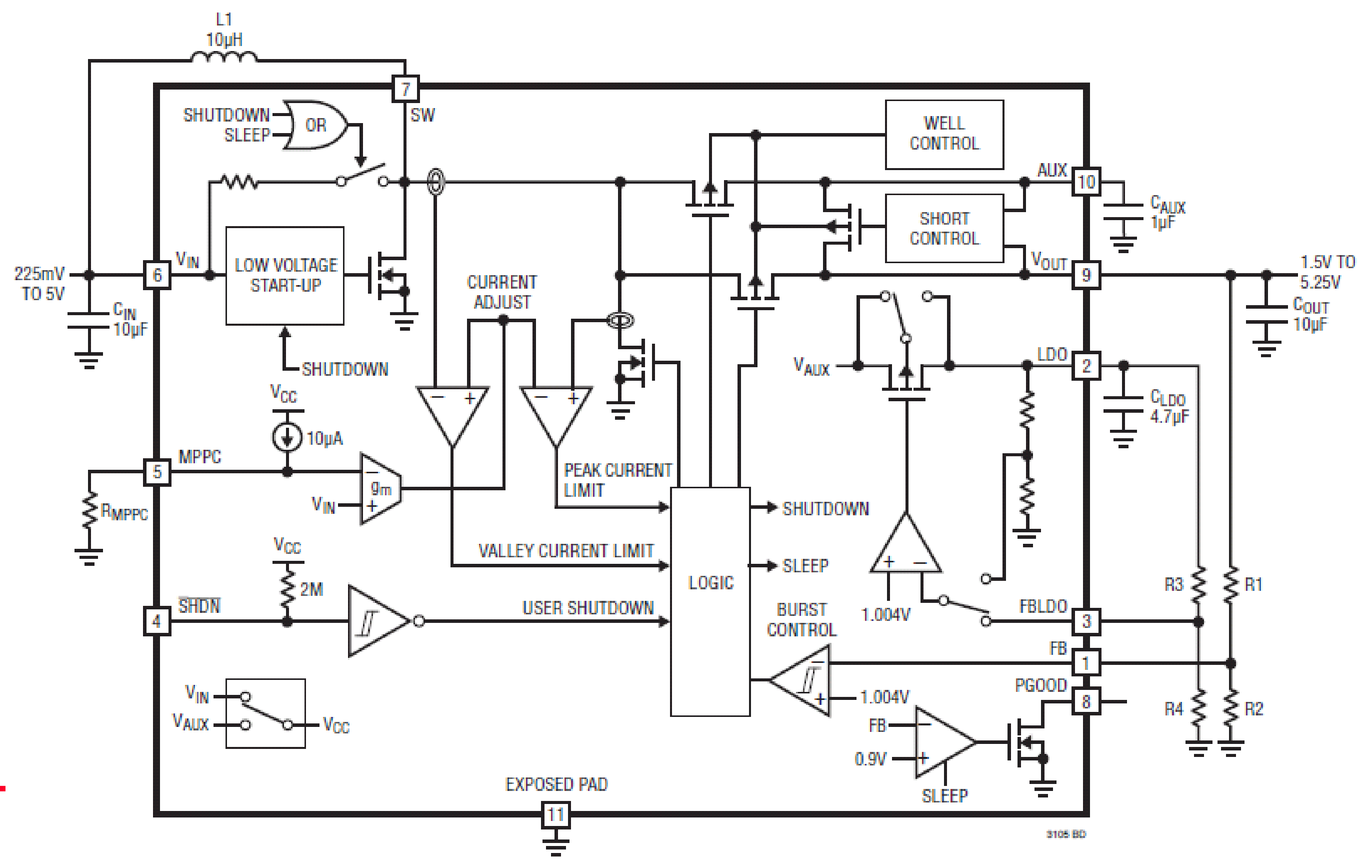
Rs = 1.6 ohms

Rp = infinity

BLOCK DIAGRAM FOR LTC3105

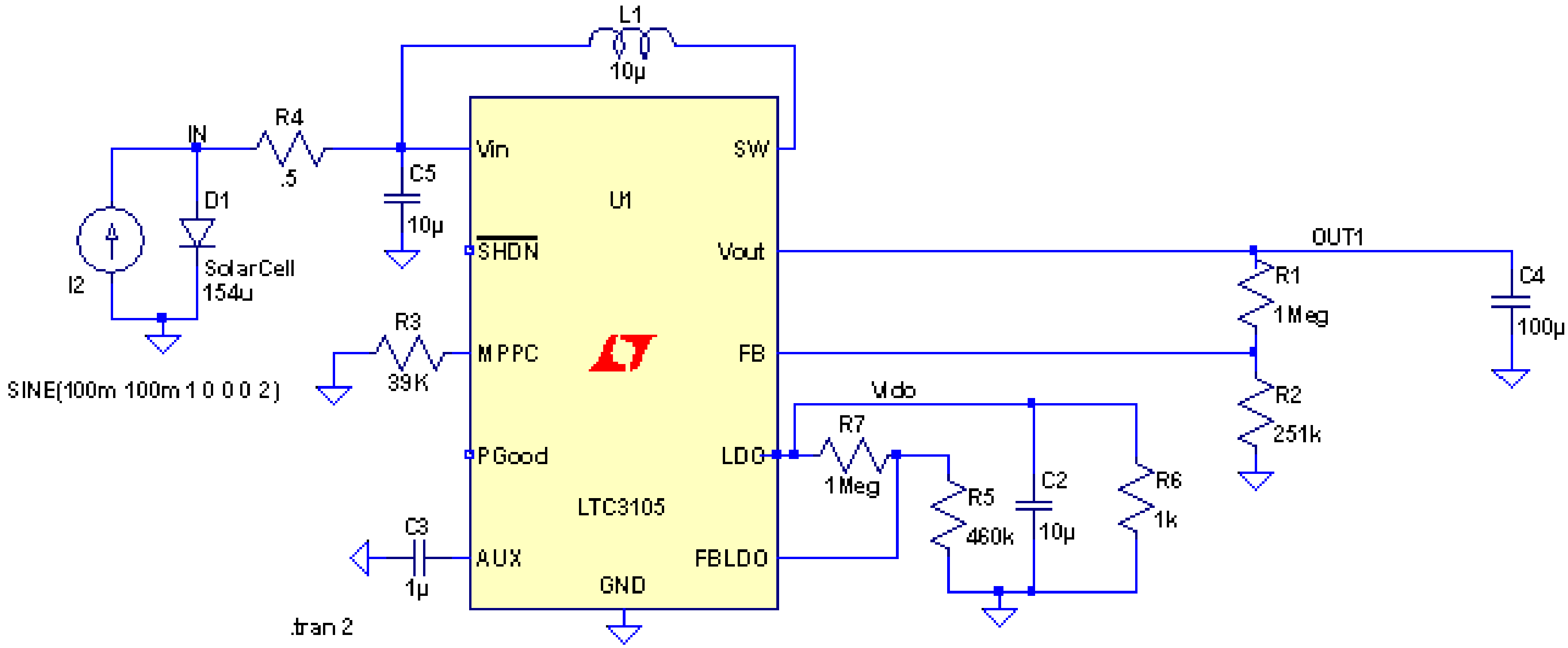
LTC3105

BLOCK DIAGRAM (Pin Numbers for DFN Package Only)



SIMULATION FOR VOUT=5 AND VLTO=3.3

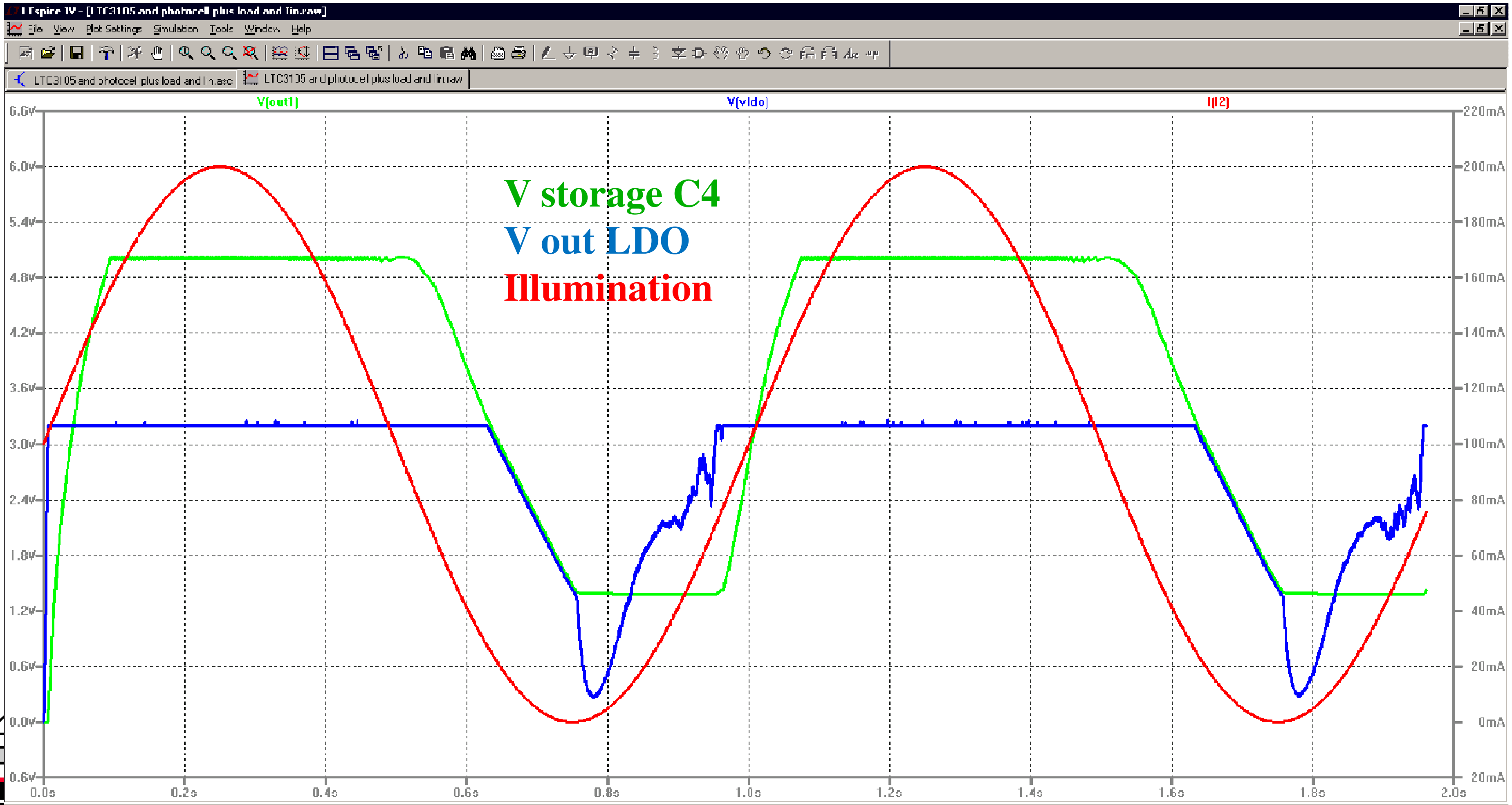
LTC3105 - 400mA Step-Up DC/DC Converter with Maximum Power Point Control and 250mV Start-Up
3.3V from Multiple Stacked-Cell Photovoltaic with Source Temperature Tracking
Input: .6V to 1V Output1: 3.3V @ 10mA Output2: 2.2V @ 6mA



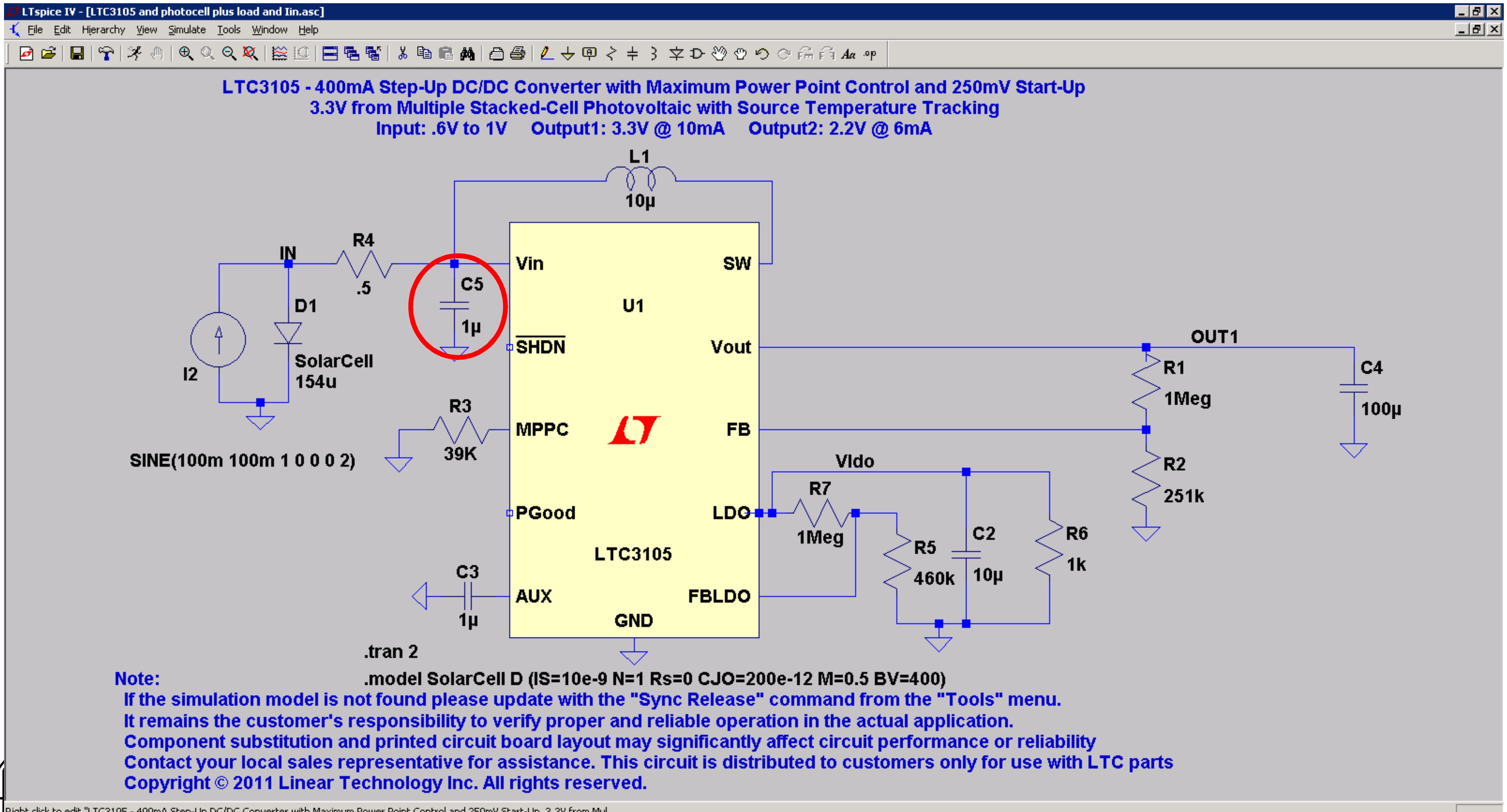
.tran 2

Note: .model SolarCell D(IS=10e-9 N=1 Rs=0 CJO=200e-12 M=0.5 BV=400)
If the simulation model is not found please update with the "Sync Release" command from the "Tools" menu.
It remains the customer's responsibility to verify proper and reliable operation in the actual application.
Component substitution and printed circuit board layout may significantly affect circuit performance or reliability
Contact your local sales representative for assistance. This circuit is distributed to customers only for use with LTC parts

SIMULATION FOR SINUSOIDAL ILLUMINATION



SIMULATION TO OPTIMIZE TO LOW LIGHT LEVELS



SIMULATION TO OPTIMIZE TO LOW LIGHT LEVELS