Ultra Efficient Energy Harvester with Battery Management, Buck Converter and 5V Linear Charger

General Description

The ET9504XXX is specifically designed to extract DC energy harvesting, high-impedance sources like photovoltaic(solar) or thermal electric generators (TEGs) without collapsing those sources. 5V input Linear Charger can also be used to charge the battery (e.g. if the battery gets depleted). This fully integrated and compact power management system allows for extending battery lifetime and eliminating the primary energy storage in a large range of applications.

The ET9504XXX has a built-in cold-start circuit, it can start operating with an input voltage as low as 275mV (min.5μW power), it makes ET9504XXX to better harvest the energy from those energy harvesting.

There is a boost from the energy harvesting to the battery. The boost can implements voltage regulation of the energy harvesting, allowing for harvesting the maximum efficiency energy harvesting from the source to the battery.

There is a buck regulator with selectable output voltage from the battery which allows an application circuit to be supplied with high efficiency.

ET9504XXX has abundant analog and digital configurable resources to meet the requirements of various customized functions.

ET9504XXX can work in shipping mode which can avoid charging and discharging of the storage element during shipping or storage.

Features

- Cold Start from 275mV / 5μW Input
    - Startup at Ultra-low Power from Harvesting Source Input
- Selectable Input Regulation Voltage of Boost for Energy Harvesting
    - Up to 110mA Current Extracted from the Harvester
- Selectable Overdischarge and Overcharge Protection
    - Supports Various Types of Rechargeable Batteries (LiC, Li-ion, LiPo...)
- Selectable Output of Buck for Application Circuit
    - Buck with Efficiency above 90%
    - Output Current up to 135mA
- Shipping Mode with less than 10nA Leakage Current of Battery

- 5V Linear Charger
  - Provide a way for Fast Charging with Pre-Charge/CC/CV Charge Mode when no Source is Available for Long Time
- Package Information:

Part No.	Package	Packing Option	MSL
ET9504XXX	DFN10 (3mm×3mm)	Tape and Reel ,3K	Level 3

Application

- Remote Control
- Portable Device
- Wearable Device
- Wireless Keyboards

Device information

ET 9504 X X X

X PV_CELL constant regulation MPPT voltage choice	**X** Storage element configuration voltage choice	**X** SYS output voltage choice
See Table 1	See Table 2	See Table 3

Table 1. PV_CELL constant regulation MPPT voltage choice

X PV_CELL constant regulation MPPT voltage choice			
X Value	$V_{PV\_CELL,REG}$	**X** Value	$V_{PV\_CELL,REG}$
0	0.25	G	1.10
1	0.30	H	1.20
2	0.35	I	1.30
3	0.40	J	1.40
4	0.45	K	1.50
5	0.50	L	1.60
6	0.55	M	1.70
7	0.60	N	1.80
8	0.65	O	1.90
9	0.70	P	2.00
A	0.75	Q	2.20
B	0.80	R	2.40
C	0.85	S	2.60
D	0.90	T	2.80
E	0.95	U	3.00
F	1.00	V	3.20

Table 2. Storage element configuration voltage choice

X Storage element configuration voltage choice				
X Value	Overdischarge voltage $V_{BAT\_UVP\_F}$ (V)	Charge ready voltage $V_{BAT\_UVP\_R}$ (V)	Overcharge voltage V_{BAT_REG} (1) (V)	Pre-Charge/CC Ratio
0	2.46	2.56	3.80	30%
1	3.00	3.20	4.12	10%
2	3.00	3.20	4.35	10%
3	3.50	3.55	3.90	10%

Note1. Above V_{BAT_REG} is for PV_CELL harvester charge;

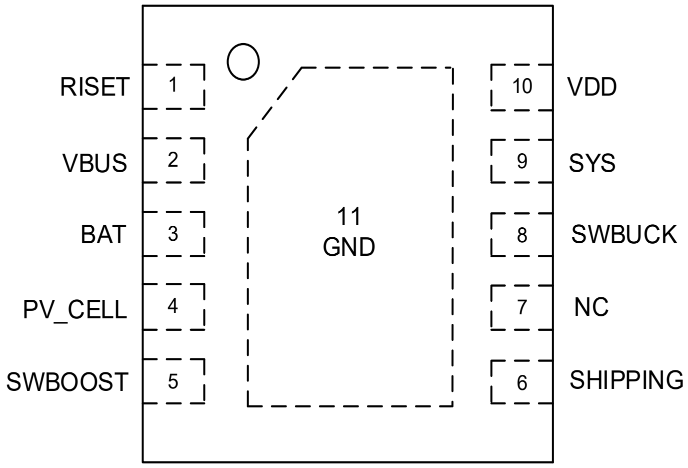
If use Linear Charger, it will be V_{BAT_REG} -60mV to protect storage element.

Table 3. SYS output voltage choice

X SYS output voltage choice	
X Value	SYS voltage V_{SYS} [2] (V)
0	OFF
1	2.2
2	2.5
3	2.8

Note2. The buck output voltage cannot be selected higher than $V_{BAT\_UVP\_F}$. As in such situation, ET9504XXX will not start the buck converter. Only when V_{SYS} set 2.8V, $V_{BAT\_UVP\_F}$ can not choose 2.46V.

Pin Configuration



Top View

Pin Function

Pin No.	Pin Name	Description
1	RISET	Connection to an external resistor to set the charging current from VBUS supply to BAT. Leave floating if the VBUS power supply is not used.
2	VBUS	DC Power Supply Input(optional).Leave floating if not used.
3	BAT	Connection to the energy storage element (rechargeable battery).
4	PV_CELL	Connection to the PV cell energy source harvested.
5	SWBOOST	Switch node connection of the boost converter.
6	SHIPPING	Logic input. When HIGH: ● Minimum consumption from the storage element. ● Boost converter is disabled ● Buck is disabled. ● VDD is charged only when energy is available on PV_CELL. Read as LOW if left floating.
7	NC	None connect.
8	SWBUCK	Switch node connection of the buck converter.
9	SYS	Output voltage of the buck converter to supply system circuit.
10	VDD	Connection for C_{VDD} buffering capacitor. Internal power supply (do not connect any external circuit on VDD).
11	GND	Ground

Simplified schematic

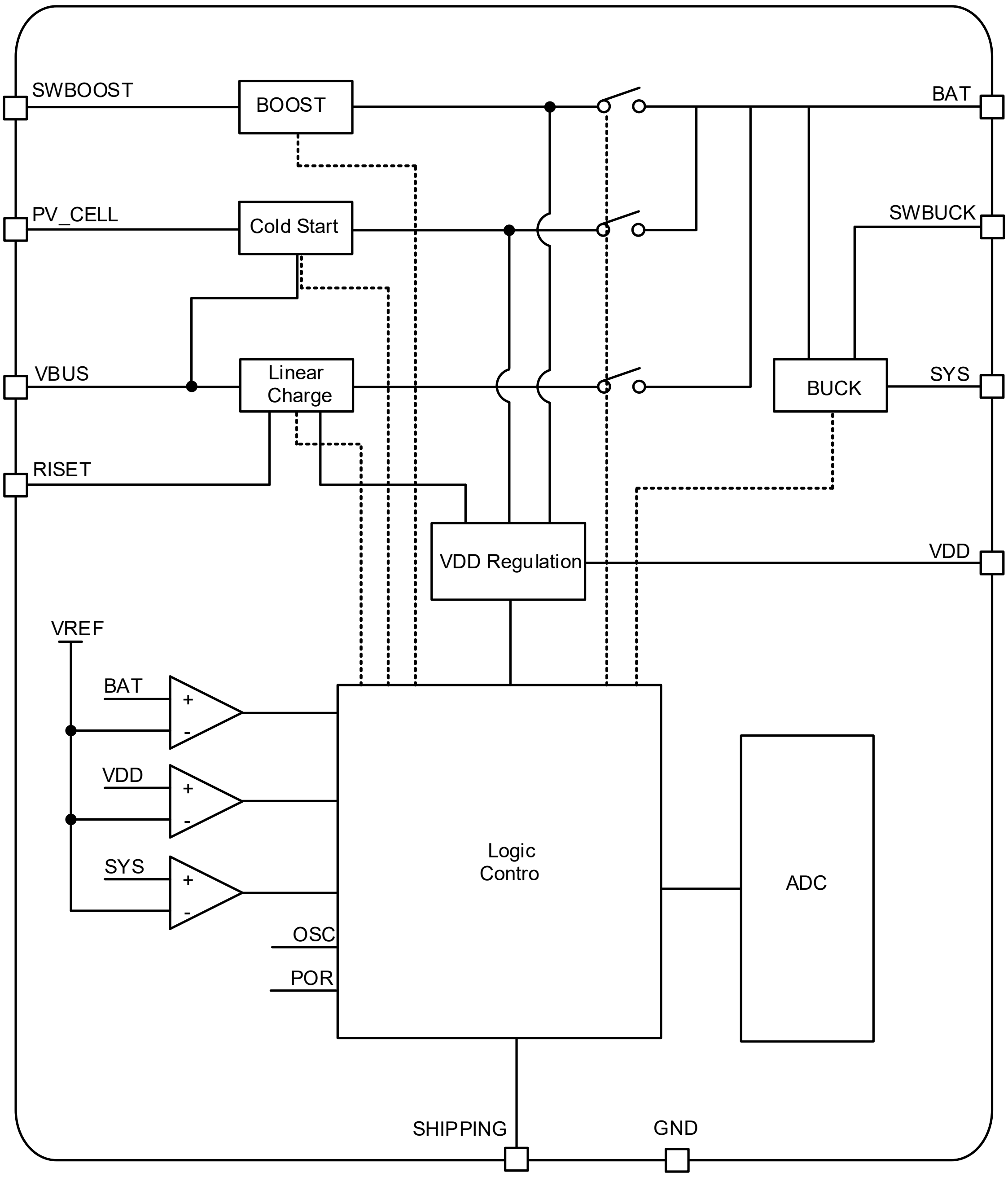


Figure 1. Simplified inside schematic

Absolute Maximum Ratings

Symbol	Parameter	Min	Typ	Max	Unit
V_{VDD}	VDD pin DC Voltage	-0.3		3.3	V
V_S	Other pins DC Voltage	-0.3		5.5	V
T_J	Operating junction temperature	-40		150	°C
T_{STG}	Storage Temperature	-65		150	°C
V_{ESD}	Electrostatic Discharge Capability(HBM)			2000	V
	Electrostatic Discharge Capability(CDM)			500	V

Maximum ratings are those values beyond which device damage can occur. Maximum ratings applied to the device are individual stress limit values (not normal operating conditions) and are not valid simultaneously. If these limits are exceeded, device functional operation is not implied, damage may occur and reliability may be affected.

Note. This device series incorporates ESD protection and is tested by the following methods:

ESD Human Body Model tested per ESDA/JEDEC JS-001-2017.

CDM tested per ESDA/JEDEC JS-002-2018.

Recommended Operating Conditions

Symbol	Parameter		Min	Typ	Max	Unit
Recommended Operating Temperature Range						
T_A	Operating Temperature Range		-40		85	°C
External components						
C_{PV_CELL}	Capacitor decoupling of PV_CELL terminal		10	22		μF
C_{SYS}	Capacitor decoupling of buck converter		10	22		μF
C_{VDD}	Capacitor decoupling of VDD terminal		4.7	10		μF
C_{BAT}	Capacitor decoupling of BAT terminal		10	47		μF
C_{VBUS}	Capacitor decoupling of VBUS terminal		1	3.3		μF
L_{BOOST}	Inductor of boost converter		10	33		μH
L_{BUCK}	Inductor of buck converter		3.3	10		μH
R_{RISET}	Resistor for configuring the 5V charger current when in constant current mode (CC). (Optional)		0.37		3.7	kΩ
Logic input pins						
SHIP_MODE	Shipping mode enable	Logic LOW (0)	Connect to GND			
		Logic HIGH (1)	Connect to BAT			

Electrical Characteristics

T_A = 25°C, unless otherwise noted.

Symbol	Parameter	Test Conditions	Min	Typ	Max	Unit
Input voltage and input power						
$P_{PV\_CELL,CS}$	Minimum source power required for cold start			5		μW
$V_{PV\_CELL,CS}$	Minimum source voltage required for cold start			0.275		V
$V_{PV\_CELL,REG}$	Target MPPT regulation voltage of the source, See Table 1		0.25		3.20 (3)	V
V_{VBUS}	Voltage on the VBUS pin to allow for Linear Charging		3.5 (4)		5.5	V
I_{SET}	Maximum charging current of Linear Charger when in constant current mode. This is programmed by the resistor on the RISET pin.		13.5		135	mA
Time parameter						
t_{DEB}	Debounce Time from V_{BAT} < $V_{BAT\_UVP\_F}$ to buck SYS turn off			2.50		s
BAT Storage element						
$V_{BAT\_UVP\_F}$	Minimum voltage accepted on BAT before stopping to supply SYS	ET9504X0X		2.46		V
		ET9504X1X/ET9504X2X		3.00		V
		ET9504X3X		3.50		V
$V_{BAT\_UVP\_R}$	Voltage required on BAT to start supplying to SYS	ET9504X0X		2.56		V
		ET9504X1X/ET9504X2X		3.20		V
		ET9504X3X		3.55		V
V_{BAT_REG}	Maximum voltage accepted on BAT before disabling its charging	ET9504X0X		3.80		V
		ET9504X1X		4.12		V
		ET9504X2X		4.35		V
		ET9504X3X		3.90		V
SYS output voltage						
V_{SYS}	SYS output voltage	ET9504XX1		2.2		V
		ET9504XX2		2.5		V
		ET9504XX3		2.8		V
Internal supply & quiescent current						
V_{VDD}	Internal voltage supply			1.8		V
$V_{VDD,RESET}$	Minimum voltage on VDD of internal circuit operation normal			1.6		V
$V_{VDD,START}$	Minimum voltage on VDD of internal circuit startup when first power-on			1.85		V
I_{BAT1}	Quiescent current on BAT in discharge Mode	SYS disabled		400		nA
		SYS enabled		650		nA

Electrical Characteristics(Continued)

T_A = 25°C, unless otherwise noted.

Symbol	Parameter	Test Conditions	Min	Typ	Max	Unit
I_{BAT2}	Quiescent current on BAT when charge done	SYS disabled		350		nA
		SYS enabled		550		nA
I_{SHIP}	Quiescent current on BAT when in shipping mode			10		nA

Note3. To harvest energy from the source, the open-circuit voltage of the PV_CELL energy source V_{OC} need higher than $V_{PV\_CELL,REG}$.

Note4. In order for 5V Linear Charger operate, VBUS voltage must be above 3.5 V and $V_{VBUS} \geq V_{BAT}$+200mV.

Functional Description

Overview

ET9504XXX has two regulated switching converters, the boost converter and the buck converter with high-power conversion efficiency. At first start-up, as soon as a required cold start voltage of 275mV and a scant amount of power of just 5μW available from the harvested energy source, then ET9504XXX cold starts.

After the cold start, the Boost starts, it will extract energy from the energy harvesting to Battery. The boost can implements voltage regulation of the energy harvesting, allowing for harvesting the maximum efficiency energy harvesting from the source to the Battery. The constant regulation MPPT voltage of PV_CELL can choose from 0.25V to 3.2V as Table 1.

When the battery voltage(V_{BAT}) higher than $V_{BAT\_UVP\_R}$, the buck converter starts up, it will supply power to the application system, and the output voltage of buck can choose 2.2/2.5/2.8V as Table 3.

A build-in 5V Linear Charger provides a way for fast charging with Pre-Charge/CC/CV Charge Mode when no source is available for a long time, and the charge parameters can choose as Table 2, the charge current is set by an external resistor of RISET pin.

Cold-Start

The ET9504XXX can cold start from PV_CELL or VBUS. The cold start circuits supply to ET9504XXX internal circuit (connected to VDD) when V_{BAT} below $V_{BAT\_UVP\_F}$. VDD is supplied by BAT when V_{BAT} high than $V_{BAT\_UVP\_F}$.

Boost Converter

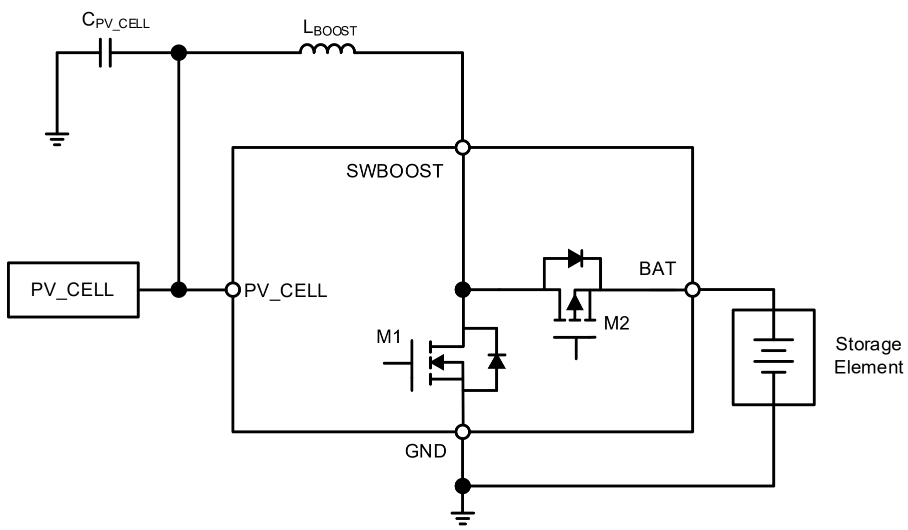


Figure 2. Simplified Schematic of boost converter

The boost converter can extract the energy from energy harvester to charge the battery.

The boost can regulate the voltage of the energy harvester to prevent the power collapse, and the voltage can choose as Table 1. An external inductor L_{BOOST} and a capacitor C_{PV_CELL} are needed. The recommended value of the L_{BOOST} is 33μH. The recommended value of the capacitor C_{PV_CELL} is 22μF which prevent the regulation voltage from the current pulses induced by the boost converter.

The inductor peak current depends on the value of L_{BOOST}.

The Boost does not work under the following conditions:

- If the open-circuit voltage of the energy harvester is lower than $V_{PV\_CELL,REG}$, the boost does not work.
- If battery voltage higher than V_{BAT_REG}, the boost does not work.

Linear Charger

The ET9504XXX has a 5V Linear Charger for fast charging of the battery with Pre-Charge/CC/CV Charge Mode. When the VBUS voltage higher than 3.5V and the BAT voltage less than V_{BAT_REG}, higher than $V_{BAT\_UVP\_R}$, the Linear Charger starts charging the battery with CC mode; If the the BAT voltage less than $V_{BAT\_UVP\_R}$, the Linear Charger starts charging the battery with Pre_Charge mode. When the BAT voltage is close to V_{BAT_REG}, the Linear Charger starts charging the battery with CV mode, at that time the charging current gradually decrease to zero as the V_{BAT} reaches V_{BAT_REG}.

The 5V Charger implements CC/CV operation. When in CC, the maximum charging current I_{SET} can be set by connecting a resistor R_{RISET} between RISET pin and GND:

$$I_{SET}=50/R_{RISET}$$

Please note that R_{RISET} must be chosen so that I_{SET} complies to the range. Example values can be found in Table 4:

Table 4. Typical resistor values for setting 5 V charger max.current

Resistor(Ω)	Maximum Charging Current(mA)
R_{RISET}	I_{SET}
370	135
680	73.5
1500	33.3
3700	13.5

Buck Converter

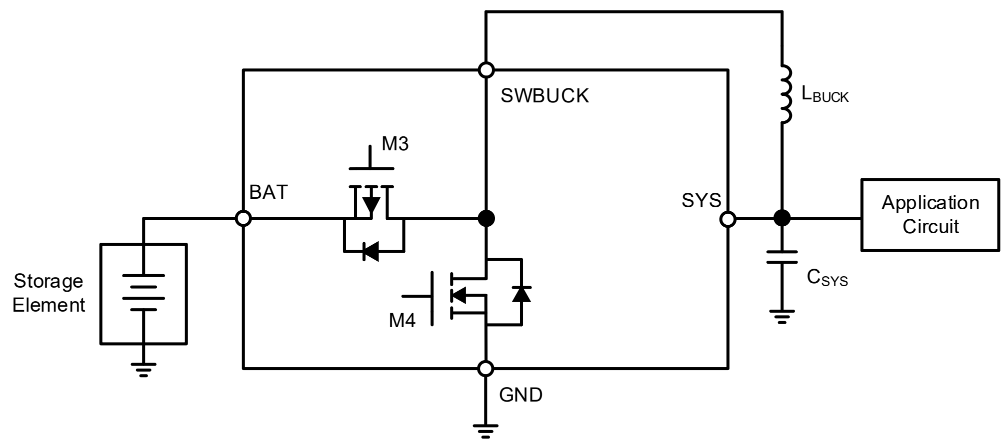


Figure 3. Simplified Schematic of buck converter

ET9504XXX provides a buck converter to extract energy from the battery to the regulated SYS output. The SYS regulation voltage V_{SYS} can choose as Table 3.

An external inductor L_{BUCK} and a capacitor C_{SYS} are needed. The recommended value of the L_{BUCK} is 10μH. The recommended value of the capacitor C_{SYS} is 22μF which prevent the regulation voltage from the current pulses induced by the buck converter.

After cold start, if the battery voltage is higher than $V_{BAT\_UVP\_R}$, the buck starts to work and supply the SYS output until the battery voltage drops below $V_{BAT\_UVP\_F}$ longer than t_{DEB}.

The buck will switch to "Hysteresis Control" mode under the following conditions:

- V_{BAT} - V_{SYS} < 0.25V.
- When V_{SYS} is too low because of load current, the "Hysteresis Control" mode enabled, making V_{SYS} rise.

State Machine Description

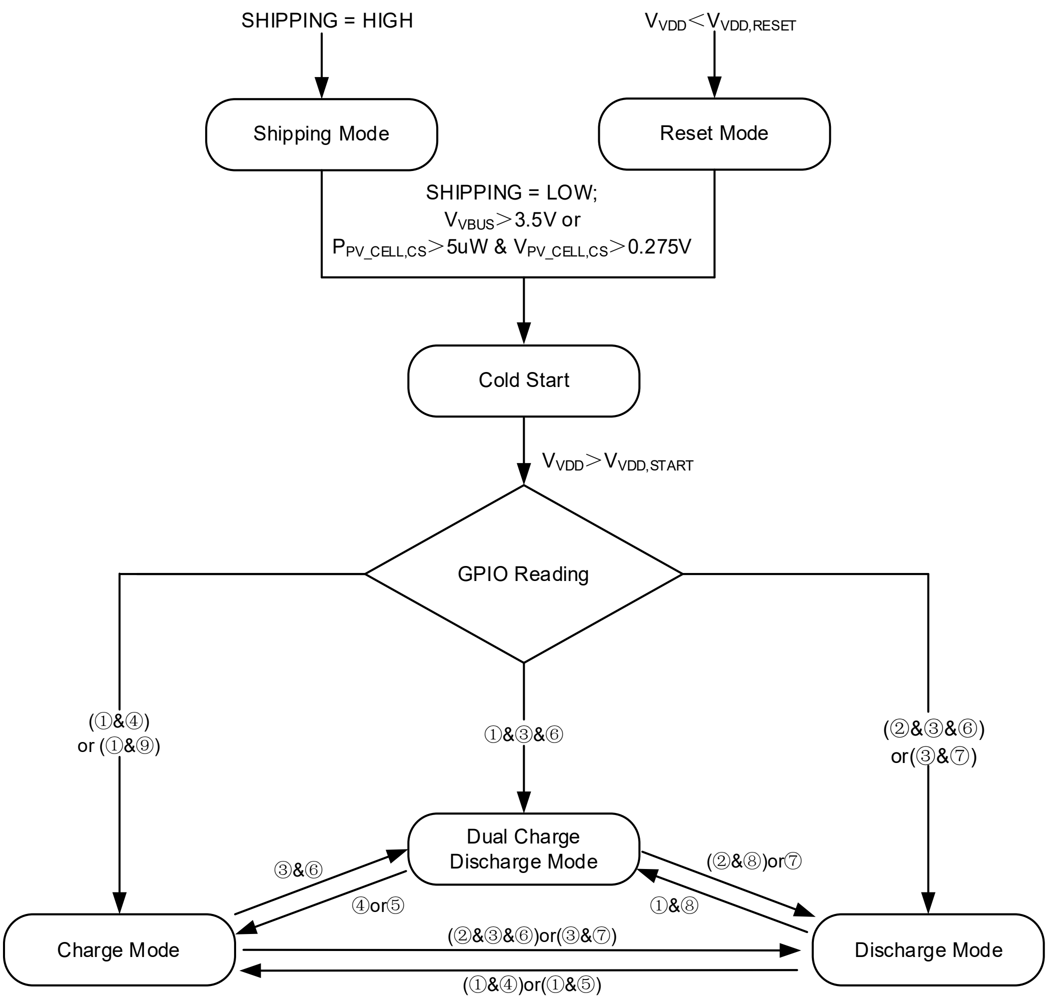


Figure 4. State Machine

① VBUS or PV CELL is on；

② No VBUS and no PV CELL；

③ V_{SYS} choose output 2.2/2.5/2.8V；

④ V_{SYS} choose OFF；

⑤ $V_{BAT} < V_{BAT\_UVP\_F}$；

⑥ $V_{BAT\_UVP\_R} < V_{BAT} < V_{BAT\_REG}$；

⑦ $V_{BAT} > V_{BAT\_REG}$；

⑧ $V_{BAT\_UVP\_F} < V_{BAT} < V_{BAT\_REG}$；

⑨ $V_{BAT} < V_{BAT\_UVP\_R}$；

➢ **Reset Mode**

The ET9504XXX enters Reset Mode under the following conditions:

- V_{DD} < 1.6V($V_{DD,RESET}$).
- Shipping mode is enabled (SHIPPING pin is HIGH).

In RESET STATE, the ET9504XXX works as follows:

- The cold start circuit of ET9504XXX starts to make V_{DD} rise to 1.85V when V_{PV_CELL} > 0.275V and $P_{PV\_CELL,CS}$ > 5μW or V_{BUS} > 3.5V
- The internal circuit supplied by VDD will be started.

The ET9504XXX stays in RESET STATE until the V_{DD} reach 1.85V. If V_{DD} < 1.6V, ET9504XXX will switch to RESET STATE again.

If shipping mode is enabled, both boost converter and buck converter are disabled, ET9504XXX stays in RESET STATE until shipping mode is disabled by setting SHIPPING LOW.

➢ **GPIO Reading**

During GPIO Reading, ET9504XXX will read the GPIO setting every time interval, and there is a build-in ADC to detect the voltage of the battery and the energy harvester, and compare with the internal reference voltage.

For ET9504XXX GPIO pin is not package out.

➢ **Charge Mode**

During Charge Mode, the battery is charged by VBUS or energy harvester, and the SYS output is disabled.

The ET9504XXX will enter into Charge Mode under the following conditions:

- VBUS or PV CELL is on.
- V_{BAT} < $V_{BAT\_UVP\_R}$ or V_{SYS} choose OFF.

➢ **Discharge Mode**

During Discharge Mode, the charge current from VBUS or energy harvester is off, and the SYS output is enabled.

The ET9504XXX will enter into Discharge Mode under the following conditions:

- V_{BAT} > V_{BAT_REG} or (no VBUS and no PV CELL).
- V_{BAT} > $V_{BAT\_UVP\_R}$ and V_{SYS} choose output 2.2/2.5/2.8V.

➢ **Dual Charge-Discharge Mode**

During Dual Charge-Discharge Mode, the battery is charged by VBUS or energy harvester, and the SYS output is enabled.

The ET9504XXX will enter into Dual Charge-Discharge mode under the following conditions:

- $V_{BAT\_UVP\_R}$ < V_{BAT} < V_{BAT_REG} and (VBUS or PV CELL is on).
- V_{SYS} choose output 2.2/2.5/2.8V.

Typical Application Circuits

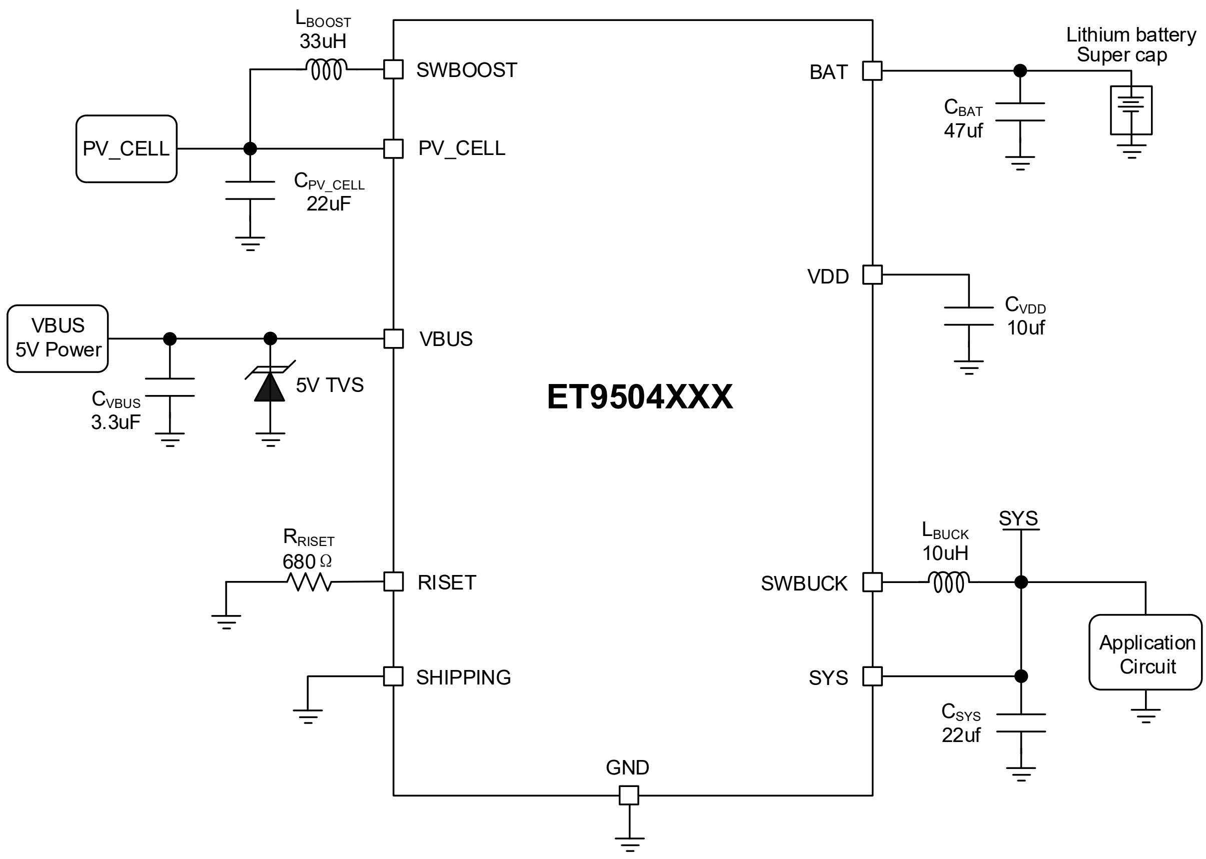


Figure 5. Typical application circuit

- **For Example——ET9504502 part：**

- PV_CELL constant regulation MPPT voltage is 0.5V.
- Storage element threshold voltages are set as follows:

  $V_{BAT\_UVP\_F}$ = 2.46V

  $V_{BAT\_UVP\_R}$ = 2.56V

  V_{BAT_REG} = 3.8V

- SYS output voltage is 2.5V.
- VBUS 5V Linear Charger current is set 73.5mA.
- SHIPPING is connected to GND,so shipping mode is not used.

Typical Operating Characteristics

BOOST conversion efficiency (L_{BOOT}=33μH):

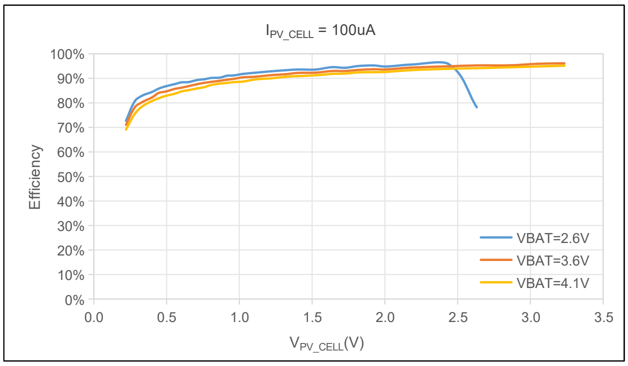


Figure 6. BOOST conversion efficiency (I_{PV_CELL}=100μA)

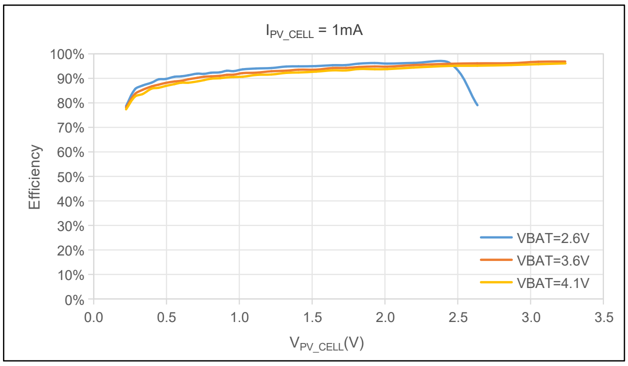


Figure 7. BOOST conversion efficiency (I_{PV_CELL}=1mA)

BUCK conversion efficiency (L_{BUCK}=10μH):

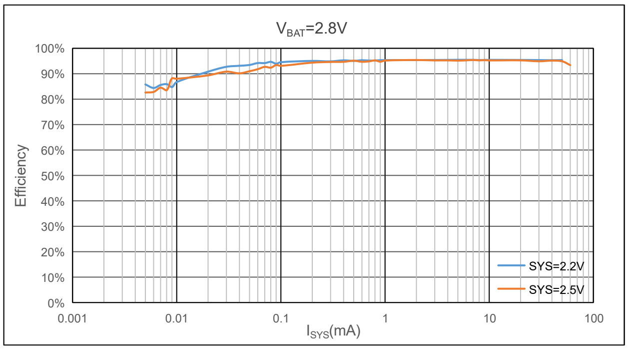


Figure 8. BUCK conversion efficiency (V_{BAT}=2.8V)

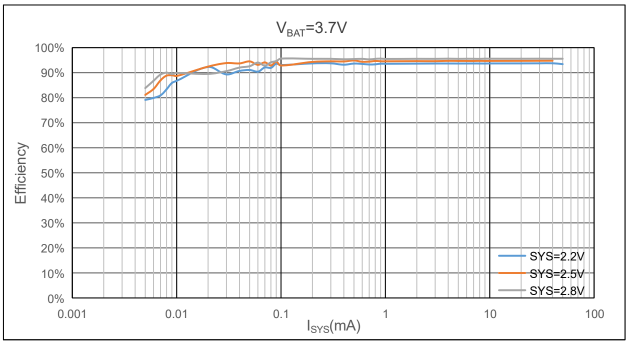
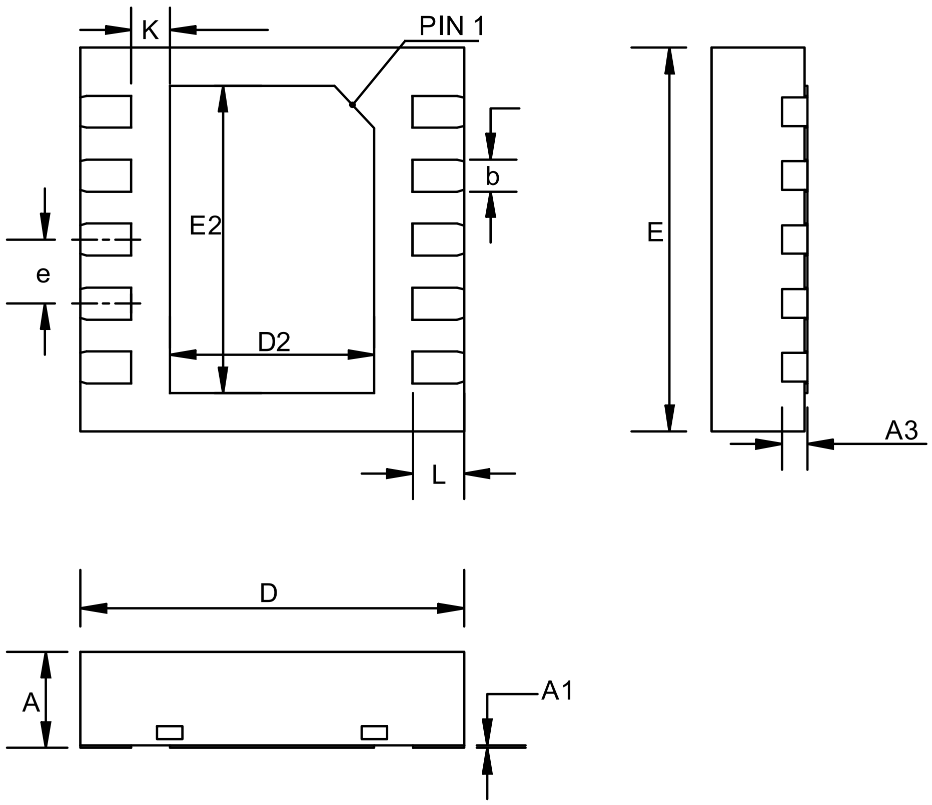


Figure 9. BUCK conversion efficiency (V_{BAT}=3.7V)

Package Dimension

DFN10(3*3)



COMMON DIMENSIONS

(UNITS OF MEASURE=MILLIMETER)

SYMBOL	MIN	NOM	MAX
A	0.70	0.75	0.80
A1	—	0.02	0.05
A3	0.203 REF		
b	0.19	0.24	0.29
D	2.90	3.00	3.10
E	2.90	3.00	3.10
D2	1.52	1.62	1.72
E2	2.38	2.48	2.58
e	0.50 BSC		
K	0.29 REF		
L	0.35	0.40	0.45

Revision History and Checking Table

Version	Date	Revision Item	Modifier	Function & Spec Checking	Package & Tape Checking
1.0	2025-07-25	Original Version	Yin Peng	Xia Yong Jie	Liu Jia Ying