ZETEX
SEMICONDUCTORS

AN40

Lithium Ion battery charging using bipolar transistors

Khagendra Thapa, Systems Engineer, Zetex Semiconductors

Introduction

Portable hand-held applications such as cell phones, PDAs, etc are becoming increasingly complex with more and more features designed into every generation. This increasing number of features combined with a requirement for smaller size and extended battery life has made Lithium batteries the preferred choice for many of these applications. Lithium batteries have improved in technology. With advances in electrodes and cell chemistries, Lithium batteries have provided a flatter discharge characteristic. More stringent requirements are being placed on manufacturers to improve charge time, maximize battery lifetime and reduce size whilst improving safety. This application note will discuss linear charge techniques and associated discrete pass elements, highlighting the dominant discrete parameters and selection criteria.

Lithium Ion (Li-Ion) battery charge cycle

In order to model the main power losses in the charging circuit with a view to select the correct components we have to understand the charge cycle of the Lithium Ion (Li-Ion) batteries. Figure 1 shows a typical charge cycle for single cell Lithium Ion batteries. The pre-charge voltage threshold, V_{PRE}, upper battery terminal voltage threshold, V_T, and recharge threshold (V_{RECHG}) depend on types of Lithium Ion batteries and manufacturers. For single cell, pre-charge voltage threshold is 2.5V or 3V and upper terminal voltage limit is 4.1 or 4.2V. These voltage differences on pre-charge and upper terminal voltage limit depend on the internal chemistry of the battery.

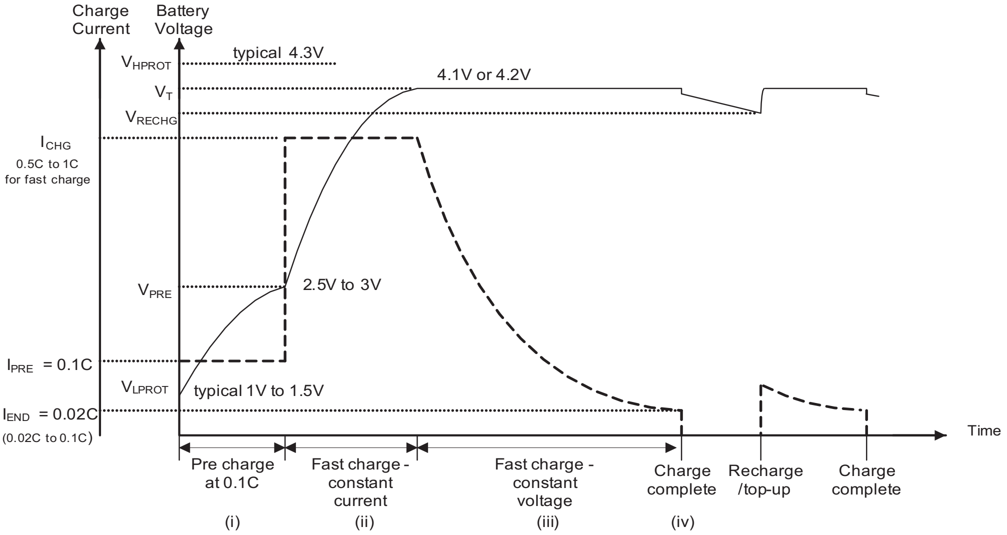

Figure 1 Typical Lithium Ion single cell charge profile

As shown in Figure 1, the typical charge cycle is split into four phases. The typical full charge cycle for a Li-Ion battery is 3 hours. V_{LPROT} and V_{HPOT} are the low and high protection voltage thresholds for the batteries with internal protection circuits.

Note: It is essential to have the proper battery specification and charge sequence requirements from the manufacturer for designing battery chargers.

i) Pre-charge phase

Deeply discharged cells require initial conditioning charge before normal fast charging can take place safely and without damage to the battery. This phase provides this initial conditioning trickle charge. Charging current is typically set to 0.1C (or as recommended by the battery manufacturer) until the battery's deep cell discharge voltage reaches its pre-charge voltage threshold, V_{PRE}. The pre-charge threshold for single cell is between 2.5V to 3V (or as recommended by the battery manufacturer) depending on the type of Li-Ion battery. If the battery voltage is already above V_{PRE} at the start of the charge cycle, the charge phase moves straight to fast charge phase.

ii) Fast charge - constant current phase

Once the pre-charge voltage threshold is reached constant current charging begins until the battery reaches its upper terminal voltage, V_T. Li-Ion batteries require a very tight tolerance on V_T, typically 1% over temperature.

For fast charge the charge rate is typically between 0.5C to 1C. The charge rate above 1C is not recommended. The charge rate above 1C reduces the battery capacity and increases the battery temperature. The charge rate above 1C does not reduce the total charge time to overall full capacity. Depending on the protection circuits within the battery, the charge rate well above 1C may not be possible.

iii) Fast charge - constant voltage phase

The fast charge phase switches constant current to constant voltage when the battery voltage reaches its upper terminal voltage threshold. The battery voltage is maintained at its upper terminal voltage threshold while the charging current decays exponentially from 1C to less than 0.1C (typically 0.02C), as a consequence of an increase in the internal impedance of the battery. This phase takes the majority of time during the batteries charging cycle.

iv) Charge termination

The termination of the charge cycle is typically by either timer or charge current decaying to end of charge current threshold, I_{END}. The end of charge current threshold is less than 0.1C, typically 0.02C (or recommended by the manufacturer). If fast charge phase continues longer than set time irrespective of the charge current, the charging is stopped.

In some linear chargers battery temperature is also monitored. If battery temperature rises above safe charging/operating temperature (as per manufacturers' specification), the charge cycle is terminated immediately irrespective of the charge status.

Recharge/top up charge

Li-Ion batteries are unable to absorb continuous over charge and therefore continuous trickle charge to fully charged battery is **not** recommended. Instead, float charge should be applied if the terminal voltage drops by certain amount, typically 100mV (or as recommended by the manufacturer) to the recharge threshold. The float charge can either initiate only the constant voltage phase or retrigger the complete charge cycle depending on the charger design and the recharge voltage threshold, V_{RECHG}.

Charger

There are three main topologies for charging the batteries, switch-mode, linear and pulse charging each with advantages and disadvantages for differing applications.

Switch-mode chargers offer the best efficiency and faster charging currents but have the disadvantage of a more complex design. Consequently they are typically used where higher charge currents are required, such as notebook computers.

Pulse chargers have seen use in Nickel (NiCd) Cadmium and Nickel-Metal Hydride (NiMH) battery charging application to reduce 'memory phenomenon' and the crystalline formation within the battery. Although well designed complex pulse chargers with protection (over voltage, temperature and current) have been used, pulse charger offer little benefit to Li-Ion battery charging. Instead, maximum pulse current and voltage peaks due to pulse current may interact with the protective system within the battery. For this reason pulse chargers are **not** recommended for Li-Ion batteries.

We will concentrate on linear battery charger in this application note.

Battery charging using linear chargers

Linear chargers are simple in design, small and have no noise associated with 'switching mode converter' making them suitable for low power and low noise applications. They use an external pass element to drop the battery voltage from the input supply to the battery voltage thus power dissipation can be high. Figure 2 shows a typical linear charger application with external pass element and reverse blocking Schottky diode.

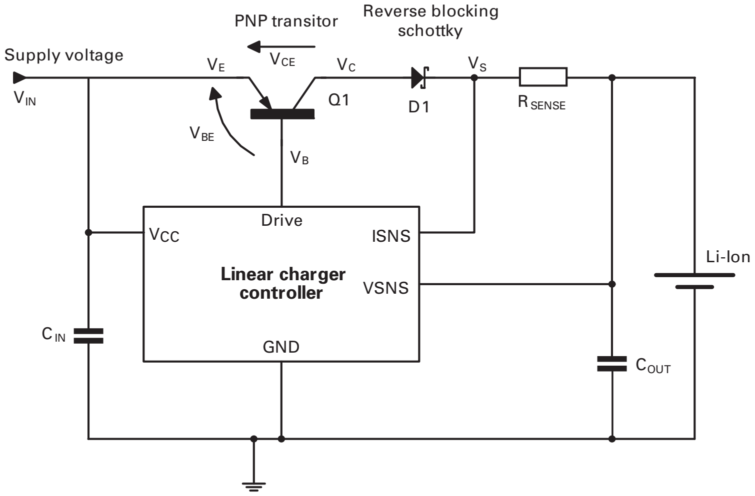

Figure 2 Typical linear battery charging application

Pass element Q1 can be either MOSFET or bipolar transistors. MOSFETs require a reverse blocking Schottky diode in series to prevent current flowing from the batteries to the supply, through its body diode. Two MOSFETs, one as pass element and the other as reverse blocking diode can also be used. However Schottky diodes are cheaper than MOSFETs as reverse blocking devices. Most PNP transistors are able to provide reverse blocking for single cell NiCd and NiMH batteries but this capability is not specified or guaranteed. Li-Ion batteries (including a single cell with 4.2V), generally, require a blocking diode in series with standard bipolar transistors. Zetex provides a range of application specific transistors which guarantee the reverse blocking capability necessary for single cell Li-Ion battery charging.

The need for additional Schottky diode for reverse blocking is an issue for linear battery charger where charging voltage head-room is low especially in the case of USB bus-powered chargers. USB supply voltage can range from 4.4V to 5.25V.

During the constant current phase the battery voltage rises, reducing the transistor collector-emitter voltage to the point where the transistor approaches the saturation region and gain starts to fall. The charge controller senses this via the sense resistor and compensates by increasing base drive, thereby maintaining charge current. The transistor saturation characteristic is therefore important in delivering the charge current at this point in the charge cycle, and must be lower than the minimum circuit voltage, taking into account the input and battery voltages, the sense resistor voltage drop plus the forward voltage of any diode used. Clearly the saturation characteristics are even more important when input voltages are low, eg 4.4V.

As an example, consider the circuit in Figure 2, where USB port output voltage is 4.75V, (the lower end of high-power USB port voltage range) and charge current is 500mA. The reverse blocking Schottky diode forward voltage drop is 0.35V. If the saturation voltage of the transistor is 0.3V, the voltage at the sense resistor, V_S, is 4.1V. Allowing for further voltage drop at sense resistor, voltage at the battery is below 4.1V and is not adequate to take the Li-Ion cell to full charge capacity. This situation is worse when supply voltage is down to 4.4V as in low-power USB ports.

Zetex' application specific transistors have very low saturation voltage and do not need a reverse blocking diode for linear charging of a single cell Li-Ion battery and thus maintain the necessary headroom.

Figure 3 shows a typical USB bus-powered single cell Li-ion linear battery charger application where a Zetex low saturation ZXTP25020CFF bipolar PNP transistor also provides the reverse blocking capability.

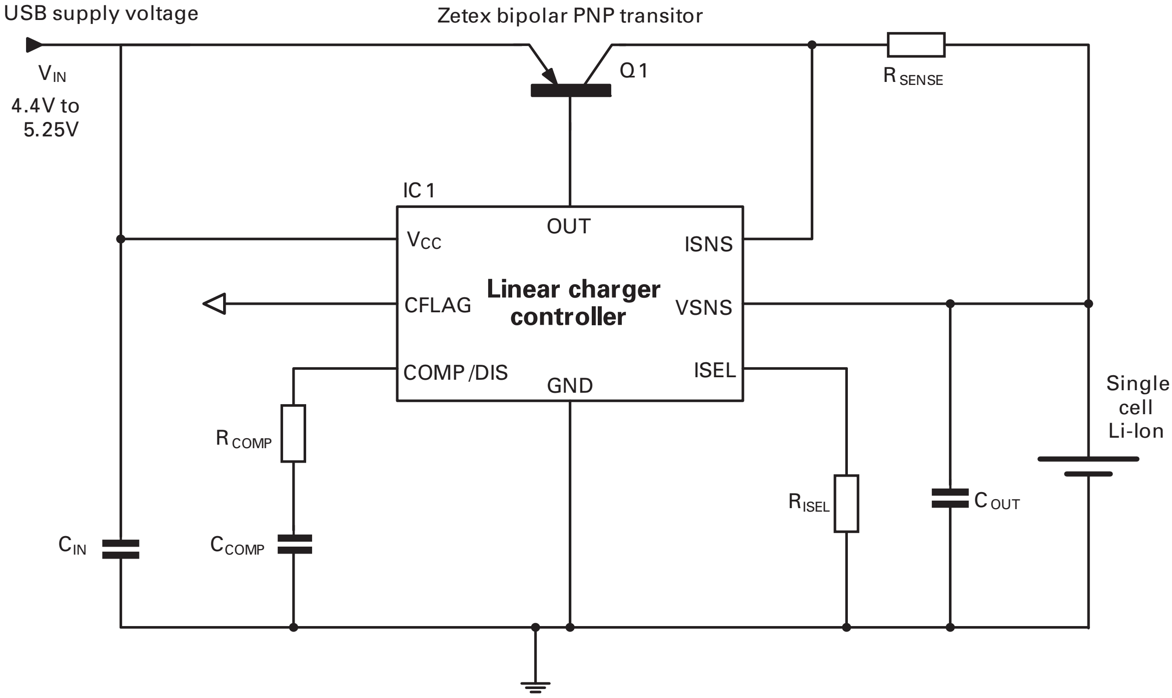

Figure 3 Charging phases

The IC1 drive capability can be typically 5mA to 50mA and may require quiescent supply current in the range of 250µA to 1mA.

Power loss calculation

The greatest power loss occurs when the charge phase enters the fast charge - constant current phase when battery is at pre-charge voltage threshold, V_{PRE}. The main power loss areas are shown with calculation example below for this normal operating highest power loss scenario.

The battery specifications for this applications example are:

Battery: single cell Li-Ion 500mAH

e.g. in portable hand held devices such as cell phones, MP3 players, etc.

Battery pre-charge threshold, $V_{PRE} = 3V$

Battery upper terminal voltage threshold, $V_T = 4.2V$

Fast charge rate 1C = 500mA.

For the example in Figure 2 component and supply specifications are:

Maximum USB Supply voltage, $(V_{IN\ MAX}) = 5.25V$

IC1 input supply current, $I_{IC\_SUPPLY\ (Max)} = 1mA$

Q1 PNP transistor = ZXTP25020CFF

Base-emitter voltage, $V_{BE} = 0.7V$

h_{FE} gain of bipolar PNP = 275 typical for collector current of 500mA at 25°C

$R_{SENSE} = 0.1\Omega$

$Pd(IC) = V_{IN\ MAX} \times I_{IC\_SUPPLY(Max)} = 5.25V \times 1mA = 5.25mW$

$Pd(SENSE) = I_{CHG}^2 \times R_{SENSE} = (0.5A)^2 \times 0.1\Omega = 25mW$

$Pd(BASE) = V_{BE} \times I_B = 0.7V \times 1.8mA = 1.27mW$

Where, $I_B = I_{CHG} / h_{FE} = 0.5A/275 = 1.8mA$ typical at 25°C.

$Pd(CE) = I_{CHG} \times (V_{IN} - V_{BAT} - V_{SENSE}) = 0.5A \times (5.25V - 3V - 0.05V) = 1.1W$

Where, $V_{SENSE} = I_{CHG} \times R_{SENSE} = 0.5A \times 0.1\Omega = 0.05V$

$Pd(TOTAL) = Pd(IC) + Pd(SENSE) + Pd(BASE) + Pd(CE) = 1.13W$

As battery voltage starts increasing, the power loss Pd(CE) reduces and so does the total power loss.

Similar calculations can be done for the start of pre-charge, fast charge - constant current and the fast charge - constant voltage phases. For the purpose of selecting the PNP transistor, the highest power loss scenario shown above has to be used to satisfy the power and thermal handling requirements. The Microsoft Excel® based linear charger performance evaluation calculator can be downloaded from **www.zetex.com/linearcalculator**

The higher the difference between the supply voltage and the battery voltage, the lower is the charger efficiency.

The maximum allowable charge current depends on the thermal capabilities of the PNP device, the thermal impedance of the board and the voltage difference between the supply voltage and the battery. The power loss needs to be matched with the thermal impedance of the PCB copper area the device is mounted on to maintain the device and the junction temperature within normal operating range.

Bipolar PNP transistor selection

For appropriate selection of the bipolar device for linear charger applications following parameters have to be considered:

- Collector-emitter break down voltage.
- Low-drop out voltage (saturation voltage) at the operating I_{CHG}/I_B condition.
  Low drop out voltage of the bipolar transistor allows batteries to be charged by a supply with low head-room (i.e. low differential voltage between the supply and the battery voltage).
- h_{FE} gain.
  To allow lower base drive from the charger IC, the bipolar devices should have a high h_{FE} gain.
- Reverse blocking voltage capability.
  The PNP transistor should provide the reverse blocking capability for a single cell Li-Ion linear battery charger. This then removes voltage headroom issues discussed above regarding USB battery charging (or similar supply voltage range) This also reduces solution cost and size by removing the need for a Shottky diode.
- The power and thermal handling capabilities of the bipolar device and its packaging.
  For portable device transistor package size is important but it still requires good power and thermal handling capabilities.

The linear charger application is subdivided into:

a) USB charging

b) Charging from low voltage output voltage DC-DC or AC-DC adapter

c) Charging from high voltage, e.g. automotive

a) USB charging

USB hub ports can provide between 100mA to 500mA depending whether the hub is USB bus-powered or self-powered. Self-powered hubs can provide up to 500mA per port while bus-powered hubs can only provide 100mA per port. The voltage supply from USB compliant port is between 4.4V to 5.25V for 100mA port and 4.75V to 5.25V for 500mA port.

The linear battery charger from USB port will have to comply with the USB voltage and the current specifications.

Bipolar PNP transistors for USB linear chargers are shown in tables 1. VB_{ECO} is the minimum rated reverse blocking voltage of the PNP transistor.

Table 1

Single cell Li-Ion, V_{PRE} = 3V; reverse blocking diode not required						
Part number	**V_{CEO} (V)**	**Min. rated BV_{EC0} (V)**	**Maximum charge current @ 5.25V input (mA)**	**h_{FE} @ $I_C/V_{CE(sat)}$ @ 25°C**	**Package**	**P_D (W)**
ZXTP25020CFF	-20	7	-600*	100 @ -0.5A/-75mV	SOT23 Flat	1.5
ZXTP25020CMA	-20	7	-600*	100 @ -0.5A/-75mV	3L-DFN 2x2mm	1.5

* The maximum current the USB hub ports can source is 500mA.

b) Charging from low voltage DC-DC or AC-DC wall adapter

Linear battery charger can be supplied by low voltage AC-DC wall adapters capable of sourcing up to 700mA. The voltage range for the wall adapter is typically 4.5V to 5.5V but can be as high as 7V. The tables 2 and 3 show bipolar PNP transistors suitable for wall adapter applications. In cases where the input voltage is high Schottky diodes can be used to share the power loss thereby allowing a higher charge current.

Table 2

Single cell Li-Ion, V_{PRE} = 3V; reverse blocking diode not required						
Part number	**V_{CEO} (V)**	**Min. rated BV_{EC0} (V)**	**Maximum charge current @ 6V input (mA)**	**h_{FE} @ $I_C/V_{CE(sat)}$ @ 25°C**	**Package**	**P_D (W)**
ZXTP25020CFF	-20	7	-500	100 @ -0.5A/-75mV	SOT23 Flat	1.5
ZXTP25020CMA	-20	7	-500	100 @ -0.5A/-75mV	3L-DFN 2x2mm	1.5

Table 3

Single cell Li-Ion, V_{PRE} = 3V; reverse blocking diode required e.g. Schottky diode ZHCS1000						
Part number	**V_{CEO} (V)**	**Min. rated BV_{EC0} (V)**	**Maximum charge current @ 6V input (mA)**	**h_{FE} @ $I_C/V_{CE(sat)}$ @ 25°C**	**Package**	**P_D (W)**
ZXTP07012EFF	-12	-	-500	100 @ -0.5A/-60mV	SOT23 Flat	1.5
ZXT2M322	-20	-	-700	100 @ -0.5A/- 150mV	3L-DFN 2x2mm	1.5

Zetex has a range of reverse blocking Schottky diodes, for instance the ZHCS1000 which has typical forward drop of 0.35V at 500mA at 25°C.

c) Charging from high voltage

Linear chargers still provide a simple low cost solution for high voltage up to 36V at low charge current up to 50mA. One example of such application would be for an external linear charger from car battery to charge hand held devices.

As the charge current is dependent on the PNP devices power and thermal handling capabilities and the voltage difference between the supply voltage and the battery, higher than 50mA charge current can be drawn from a supply lower than 36V.

For automotive application, additional protection against load dump is required.

Table 4

Single cell Li-Ion; reverse blocking diode required, e.g. Schottky diode ZHCS1000						
Part number	**V_{CEO} (V)**	**Min. rated BV_{EC0} (V)**	**Maximum charge current at 36V (mA)**	**hfe @ $I_C/V_{CE(sat)}$ @ 25°C**	**Package**	**P_D (W)**
ZXTP2012Z	-60	-	-50	50 @ -0.05A/-40mV	SOT89	2.1
ZXTP2012G	-60	-	-50	50 @ -0.05A/-40mV	SOT223	3

Conclusion

From the power dissipation breakdown calculations, the dominant loss in the charger circuit during all phases of the linear battery charging cycle is the on state loss of the pass element. The power dissipated in the fast charge phase is most significant reaching its peak when the Li-Ion battery is at pre-charge voltage threshold and the constant current charge phase is initiated. The key parameters to consider in the pass element are the power and thermal ratings, saturation voltage, reverse blocking capability and packaging. Zetex' application specific low saturation voltage bipolar PNP transistors provide reverse blocking while maintaining the necessary charging voltage head-room for single cell Li-Ion linear charger application.

Intentionally left blank

Definitions

Product change

Zetex Semiconductors reserves the right to alter, without notice, specifications, design, price or conditions of supply of any product or service. Customers are solely responsible for obtaining the latest relevant information before placing orders.

Applications disclaimer

The circuits in this design/application note are offered as design ideas. It is the responsibility of the user to ensure that the circuit is fit for the user's application and meets with the user's requirements. No representation or warranty is given and no liability whatsoever is assumed by Zetex with respect to the accuracy or use of such information, or infringement of patents or other intellectual property rights arising from such use or otherwise. Zetex does not assume any legal responsibility or will not be held legally liable (whether in contract, tort (including negligence), breach of statutory duty, restriction or otherwise) for any damages, loss of profit, business, contract, opportunity or consequential loss in the use of these circuit applications, under any circumstances.

Life support

Zetex products are specifically not authorized for use as critical components in life support devices or systems without the express written approval of the Chief Executive Officer of Zetex Semiconductors plc. As used herein:

A. Life support devices or systems are devices or systems which:
   1. are intended to implant into the body

or
   2. support or sustain life and whose failure to perform when properly used in accordance with instructions for use provided in the labelling can be reasonably expected to result in significant injury to the user.

B. A critical component is any component in a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or to affect its safety or effectiveness.

Reproduction

The product specifications contained in this publication are issued to provide outline information only which (unless agreed by the company in writing) may not be used, applied or reproduced for any purpose or form part of any order or contract or be regarded as a representation relating to the products or services concerned.

Terms and Conditions

All products are sold subjects to Zetex' terms and conditions of sale, and this disclaimer (save in the event of a conflict between the two when the terms of the contract shall prevail) according to region, supplied at the time of order acknowledgement.

For the latest information on technology, delivery terms and conditions and prices, please contact your nearest Zetex sales office .

Quality of product

Zetex is an ISO 9001 and TS16949 certified semiconductor manufacturer.

To ensure quality of service and products we strongly advise the purchase of parts directly from Zetex Semiconductors or one of our regionally authorized distributors. For a complete listing of authorized distributors please visit: **www.zetex.com/salesnetwork**

Zetex Semiconductors does not warrant or accept any liability whatsoever in respect of any parts purchased through unauthorized sales channels.

ESD (Electrostatic discharge)

Semiconductor devices are susceptible to damage by ESD. Suitable precautions should be taken when handling and transporting devices. The possible damage to devices depends on the circumstances of the handling and transporting, and the nature of the device. The extent of damage can vary from immediate functional or parametric malfunction to degradation of function or performance in use over time. Devices suspected of being affected should be replaced.

Green compliance

Zetex Semiconductors is committed to environmental excellence in all aspects of its operations which includes meeting or exceeding regulatory requirements with respect to the use of hazardous substances. Numerous successful programs have been implemented to reduce the use of hazardous substances and/or emissions.

All Zetex components are compliant with the RoHS directive, and through this it is supporting its customers in their compliance with WEEE and ELV directives.

Product status key:

"Preview"	Future device intended for production at some point. Samples may be available
"Active"	Product status recommended for new designs
"Last time buy (LTB)"	Device will be discontinued and last time buy period and delivery is in effect
"Not recommended for new designs"	Device is still in production to support existing designs and production
"Obsolete"	Production has been discontinued

Datasheet status key:

"Draft version"	This term denotes a very early datasheet version and contains highly provisional information, which may change in any manner without notice.
"Provisional version"	This term denotes a pre-release datasheet. It provides a clear indication of anticipated performance. However, changes to the test conditions and specifications may occur, at any time and without notice.
"Issue"	This term denotes an issued datasheet containing finalized specifications. However, changes to specifications may occur, at any time and without notice.

Zetex sales offices

Europe

Zetex GmbH
Kustermann-park
Balanstraße 59
D-81541 München
Germany
Telefon: (49) 89 45 49 49 0
Fax: (49) 89 45 49 49 49
europe.sales@zetex.com

Americas

Zetex Inc
700 Veterans Memorial Highway
Hauppauge, NY 11788
USA

Telephone: (1) 631 360 2222
Fax: (1) 631 360 8222
usa.sales@zetex.com

Asia Pacific

Zetex (Asia Ltd)
3701-04 Metroplaza Tower 1
Hing Fong Road, Kwai Fong
Hong Kong

Telephone: (852) 26100 611
Fax: (852) 24250 494
asia.sales@zetex.com

Corporate Headquarters

Zetex Semiconductors plc
Zetex Technology Park, Chadderton
Oldham, OL9 9LL
United Kingdom

Telephone: (44) 161 622 4444
Fax: (44) 161 622 4446
hq@zetex.com

© 2007 Published by Zetex Semiconductors plc

© Zetex Semiconductors plc 2006