ESR (Equivalent Series Resistance) Meter

Guy Fernando (M0OOX) presents in this article, instructions to build an ESR (Equivalent Series Resistance) meter for testing the health of electrolytic capacitors. The instrument displays capacitance and ESR on a digital LCD readout, with an optional audible tone indicating the condition of the capacitor under test. At the heart of the meter is a 14-pin PIC microcontroller, using just a handful of other cheap components a feature rich ESR meter is easily constructed.

- Capacitance range 0.1uF to 100,000uF
- ESR range 0.01Ω to 50Ω
- Testing frequency 100kHz or 50kHz
- Low test voltage for in-circuit testing
- Audible test result tones
- Auto power down
- Automatic testing of capacitor
- Probe resistance compensation
- Battery supply voltage compensation
- Capacitor stored charge protection
- Low and high battery warning
- Open / short circuit probe detection

Anyone who services and repairs electronic equipment knows that it is more often than not the case that an electrolytic capacitor is the culprit of a faulty piece of equipment. Aluminium electrolytic capacitors degrade with heat and age caused by the "wet" electrolyte drying out. This has the effect of reducing the capacitor's rated capacitance and increasing the capacitor's ESR, causing the equipment to malfunction. A combined capacitance and ESR meter is certainly a indispensible instrument on the test bench.

There is a good selection of ESR meters available, ranging from the very accurate although somewhat expensive, to the more reasonably priced but missing features such as the ability to perform in-circuit testing of capacitors. The author not having a suitable ESR meter, decided to design a low cost single chip solution with these advanced features built in, that would rival commercially available products, and can be easily built by any competent amateur electronics constructor.

Due to the way capacitors are physically constructed, good ESR readings typically depend upon the capacitor's value, such that larger valued capacitors usually exhibit a lower ESR. The logarithm of ESR versus the logarithm of capacitance can be treated as a linear relationship as depicted by the graph shown in Figure 1. A capacitor under test whose plotted value falls on the bottom left half of the graph can be considered "good", and conversely "bad" if the value falls in the top right half. Capacitors who's value falls in-between the two halves are considered "fair".

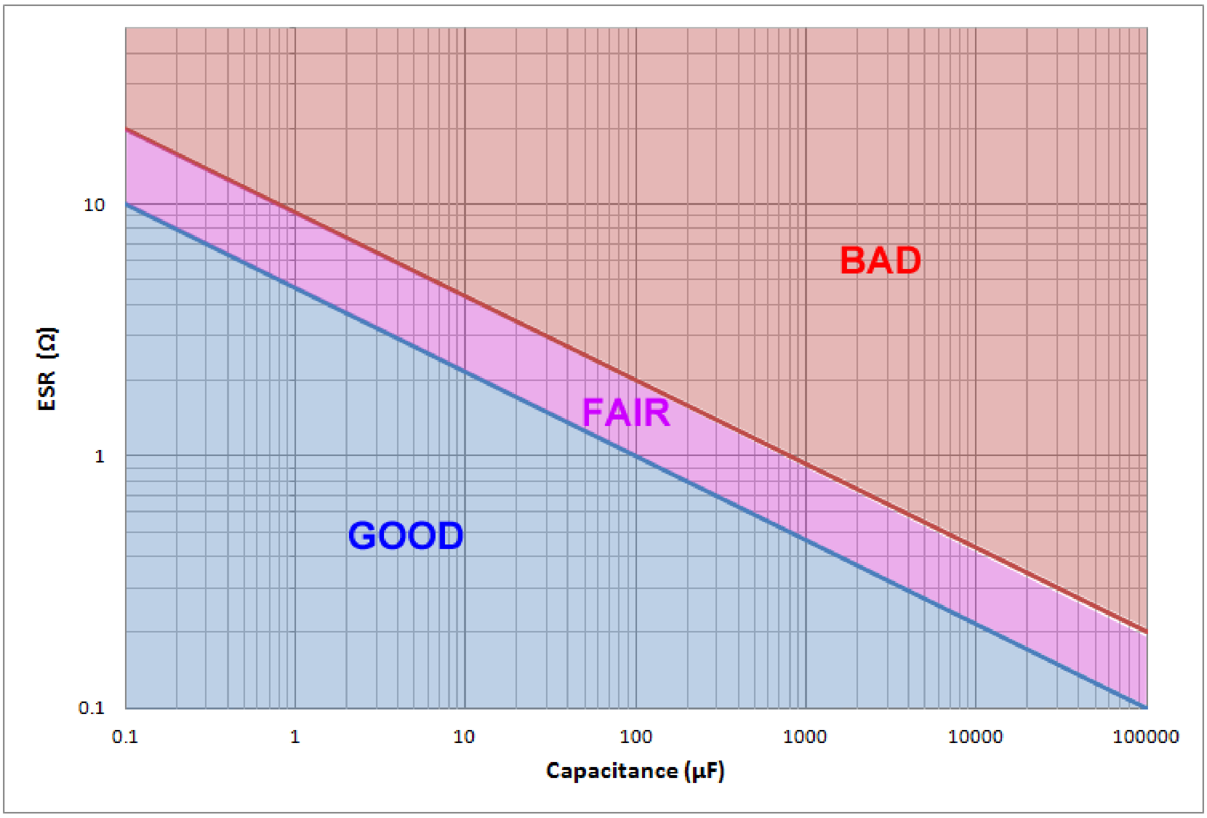
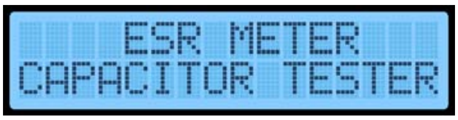


Figure 1 - Relationship between capacitor condition, capacitance and ESR

ESR Meter Operating Guide

Meter Operation

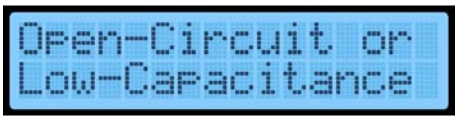
The ESR Meter is turned on by pressing the "ON/OFF" button. The backlight will illuminate and the following message will be displayed, followed by additional start up information such as the firmware version and battery voltage. The meter will sound an audible beep to indicate when ready.



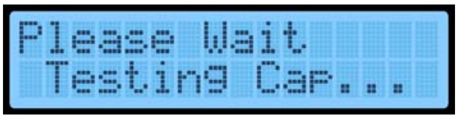
To ensure best accuracy the meter will first require calibrating, if not already done so, please refer to the "Meter Calibration" section below.

Capacitor Testing

The meter automatically performs testing when a capacitor is connected to the probes - no button presses are required during testing. When there is no capacitor connected the following message will be displayed.



Ensure the capacitor under test is first discharged before connecting it to the probes Although electrolytic capacitors are polarised, it makes no difference which way around the capacitor is connected. The following message will then be displayed, indicating that the testing is in progress.



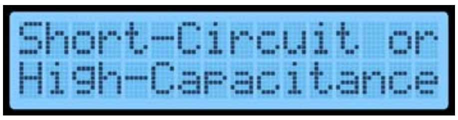
After a second or so the results of the capacitor under test are displayed. Note that large valued capacitors take a little longer. If the testing process is taking too long, the current test cycle can be cancelled by briefly pressing the "ON/OFF" button.

In the above example, the capacitance is shown to read 103µF with an ESR of 0.22Ω, which is considered a capacitor in "GOOD" condition. Unhealthy capacitors exhibit higher ESR readings which will result in "FAIR" or "BAD!" condition being displayed instead. The relationship between condition, capacitance and ESR is shown in Figure 1.

The meter also produces an audible sound (if un-muted) also indicating the test result.

GOOD	High blip
FAIR	Low blip
BAD!	High blip then low beep

If the capacitor under test is completely faulty such that it is either open-circuited or short-circuited, then either the "Open-Circuit or Low-Capacitance" or the "Short-Circuit or High-Capacitance" message will be displayed.

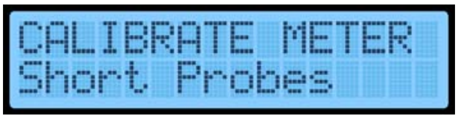


To turn the meter off (standby), depress the "ON/OFF" button until the following message is displayed.

Meter Calibration

To ensure good measurement repeatability, particularly when measuring capacitors with low values of ESR, it is advisable to regularly calibrate the meter to compensate for any probe resistance.

To perform this, press both the "ON/OFF" and the "MENU" buttons simultaneously together. After releasing both buttons the following message will be displayed.



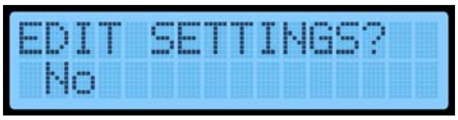
Short both probes by connecting them together ensuring that a solid connection is formed.

Then press any button to continue.

Disconnect the probes. The meter will now be calibrated to compensate for residual probe resistance. The calibration data will be stored by the microcontroller even when the meter is turned off or the batteries removed.

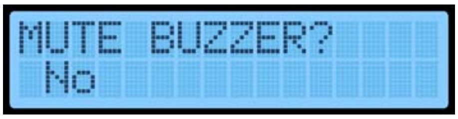
Meter Settings

To change any of the meter settings press the "MENU" button after which the following message will be displayed.



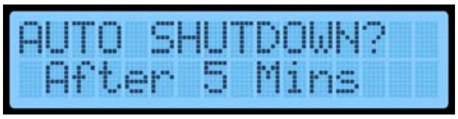
Press the "ON/OFF" button to select "Yes", then press "MENU" again to enter the settings menu.

Pressing the "ON/OFF" button will cycle through the available ESR FREQUENCY options. These being "50kHz" or "100kHz". Mostly the industry standard 100kHz frequency should be selected, however in certain circumstances 50kHz can also be used. Press the "MENU" button to continue to the next menu setting.

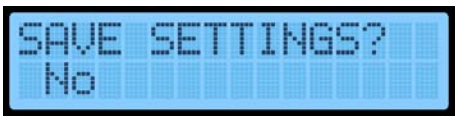


Pressing the "ON/OFF" button will cycle through the available MUTE BUZZER options. These being "Yes" or "No". Press the "MENU" button to continue to the next menu setting.

Pressing the "ON/OFF" button will cycle through the available SPLASH SCREEN options. These being "Off" or "On". If "Off" is selected the information when the meter is turned on will not be shown. Press the "MENU" button to continue to the next menu setting.



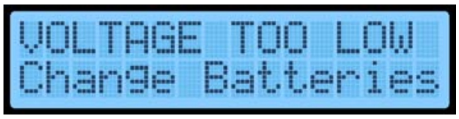
Pressing the "ON/OFF" button will cycle through the available AUTO SHUTDOWN options. These being "Never", "After 1 Min", "After 5 Min", "After 15 Min", or "After 1 Hour". Press the "MENU" button to continue to the next menu setting.



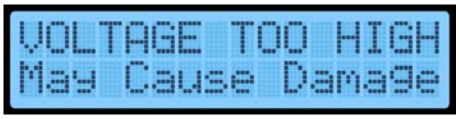
The final menu setting allows the changes just made to be saved. Pressing the "ON/OFF" button will cycle through the available SAVE SETTINGS options. These being "Yes" or "No". If "Yes" is selected then the changes will be remembered even if the meter is turned off or the batteries are removed. If "No" is selected the changes will be remembered only for the duration that the meter is on.

Other Messages

The meter is intended to operate using a battery supply close to 5.0v. If the battery voltage falls below 4.6v the meter will not be able to operate. If the following message is displayed the four AA Ni-MH batteries must be replaced with a new set.



Conversely, if the battery voltage exceeds 5.6v the meter's microcontroller could be damaged. If the following message is displayed remove the batteries immediately and replace with the correct four AA Ni-MH batteries.



How it works

Referring to Figure 2, at the heart of the hardware is a Microchip PIC16F1705 8-bit microcontroller. This PIC as well as executing the firmware code also hosts various on-chip analogue peripheral devices, including an op-amp, comparator, timer and analogue to digital converter. As a result a sophisticated test instrument can be realised using a minimal of additional discrete components.

A test stimulus signal from the PIC is sourced out of the RA5 pin and fed into the potential divider consisting of R1 and R2, to attenuate the stimulus to just 150mV. This is a sufficiently low enough voltage to allow for the testing of capacitors in-circuit, as it is well below the forward bias voltage of both silicon and germanium semiconductor devices. The PIC pins RC3, RC4 and RC5 are configured as a non-inverting op-amp with a gain of x32, as defined by R3 and R4 feedback resistors, allowing the 150mV stimulus to be amplified prior to digitisation. The two ultrafast diodes D1 and D2, serve to protect the meter in case the capacitor under test is inadvertently charged.

The firmware code deals with the evaluation of ESR and capacitance differently, and are tested independently. First the ESR is tested, this is achieved by driving high frequency square wave across the capacitor. The sensed AC peak to peak voltage will be proportional to the capacitor under test's ESR. Due to the parallel / series combination of R1, R2 and the capacitor's ESR, a non-linear relationship exists between the ADC output and ESR value, and so linearization is performed as part of the ESR calculation. Next the capacitance is tested, this is achieved by setting the RA5 pin high, thus charging the capacitor under test. The PIC's comparator non-inverting input is set to 4.096v via the internal voltage reference, and so the comparator output will go high after a period dependent on the capacitor size. The PIC's timer is loaded with zero in software and counts up until inhibited by the timer gating when the comparator's output goes high. To cover 7 decades of capacitance (i.e. 0.1uF to 100,000uF), a 32bit counter has been used. The PIC only has a 16-bit counter, but by using an overflow interrupt on the timer, further counting above a million is made possible. The capacitance value is proportional to the final counter value.

User interface text to be displayed on the HD44780 compatible 16x2 I2C LCD module is sent via the PIC pins RA0 and RA1 for SCL and SDA respectively. The I2C interface was chosen to significantly reduce the number of I/O pins required to drive the display, allowing for a low pin count 14-pin PIC to be used. Power to the LCD module is switched by the PIC pin RC2 to prevent the display from drawing current when the meter is put turned off into low power mode.

The two switches SW1 and SW2 are polled by the firmware to accept user commands. The use of the PIC's internal pull-up resistors save having to use two additional external resistors. The PIC pin RC1 is configured to output drive mixed audible frequencies to the piezo buzzer BZ1 via the limiting resistor R5.

To further keep the component count down and for simplicity reasons, the meter is directly powered by four AA Ni-MH rechargeable batteries, each cell nominally 1.2v, yielding a typical supply voltage of 4.8v. If it is intended to power the meter using four alkaline AA cells, each cell nominally 1.5v, then a silicon diode must be placed in series with the battery to reduce the supply voltage from 6.0v to around 5.4v, a voltage at which the PIC can tolerate. The meter can also be made to be mains powered using a suitable 5v DC wall adapter.

The meter's operating current is approximately 20mA, and 15µA during power off (standby).

The Firmware

Programming a blank microcontroller with the firmware requires specialised software and programmer equipment that most readers will not have access to. For this reason a pre-programmed PIC16F1705 PIC microcontroller can be obtained from the author's website at:

http://www.i4cy.com/m0oox/esrmeter

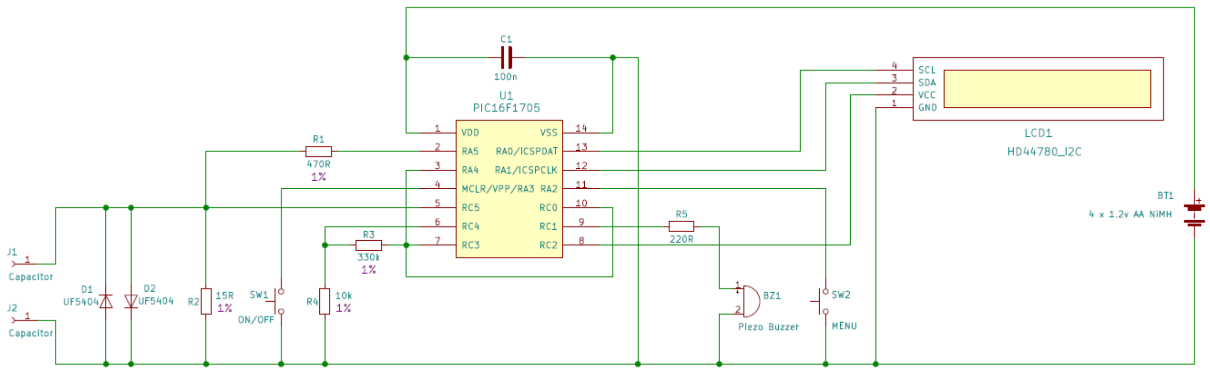


Figure 2 - Schematic Diagram

Parts List

C1	100n
R1	470R 1% 0.25W
R2	15R 1% 0.25W
R3	330k 1% 0.25W
R4	10k 1% 0.25W
R5	220R 5% 0.25W
D1,D2	UF5404
U1	PIC16F1705 (Available pre-programmed, see http://www.i4cy.com/m0oox/esrmeter)
LCD1	HD44780 I2C. Compatible 1602 LCD Module with PCF8574 I2C daughter board
BZ1	Piezo buzzer
SW1,SW2	Momentary tactile push buttons
BT1	4 x 1.2v Ni-MH AA batteries
J1,J2	4mm panel mount banana sockets
IC Socket	14-pin low profile DIP
Veroboard	Copper strip board 13 x 34 holes, 0.1" pitch
Veropins	9off. Vero part 18-1658
Screws	2off. M2 x 5mm pan head self tapper
Wire	Insulated stranded 7/0.2mm 1000V PVC Ø1.2mm Insulated stranded 24/0.2mm 1000V PVC Ø2.3mm Tinned copper un-insulated 22SWG Ø0.71mm
Enclosure	OKW Part# A9074207, DATEC-MOBIL-BOX M (or similar) OKW Part# A9345217, Set of battery compartment, 4 x AA (or similar)

Construction

The main-board layout attempts to minimise digital noise and earth loops problems by separating the analogue grounds from the digital grounds. The main-board is constructed on copper strip board (veroboard) with components positions placed as shown in Figure 3. Cut a piece of strip board so that it has 13 strips by 34 holes wide. Referring to Figure 3, begin by soldering the discrete components, the resistors and decoupling capacitor. Then solder the 8 un-insulated tinned wires shown as grey vertical lines.

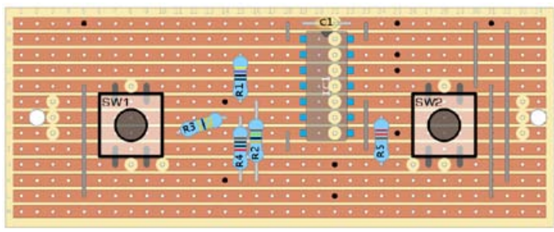


Figure 3 - Main-board layout

Next solder the IC socket and the two buttons as shown making sure the switch contacts are correctly oriented. Push the 9 veropins through from the top of the board as shown as black dots, then solder each pin to the copper tracks below. Using an appropriate tool or drill bit, cut the tracks between the pins of IC1, C1 and the switches. There are 20 cut tracks in total, 6 of which isolate the holes for the two mounting screws for the board.

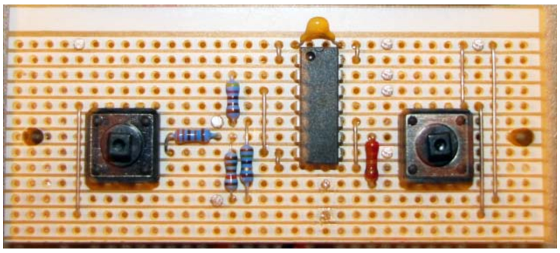


Photo 1 - Main-board construction

Now carefully insert the pre-programmed PIC into the DIP socket while observing appropriate anti-static precautions, and ensuring that the semi-circular notch on the IC is correctly oriented at the top.

It is entirely up to the reader to choose how to house the meter components depending on the enclosure chosen. The author used the following method, having a DATEC-MOBIL-BOX enclosure to hand.

Referring to Figure 5, using a colour printer print off the front panel artwork scaling the rectangular edges to 80mm x 167mm. Apply double sided sticky tape to the rear of the panel artwork, and protective sticky back plastic to the front of the panel artwork. Using scissors and a knife, carefully cut around the panel artwork edges, and make the cut-outs for the LCD and banana sockets.

Drill two mounting holes in the main-board as shown in Figure 3. Screw down the main-board and LCD display to the inside of the front enclosure section. Carefully hot glue the buzzer to the inside surface of the front enclosure section. Using the panel artwork as a template, drill 4 holes in the front enclosure section for the 2 switches and 2 banana sockets. Peel off the double sided sticky tape from the panel artwork and attach to the front of the enclosure. Fit the 2 banana sockets to the front enclosure section.

Referring to
Figure 4, solder D1 and D2 back to back onto the lugs of the banana sockets. Using the thicker insulated wire also solder to each lug and connect to the appropriate veropins on the underside of the main-board. It is important that thick wire is used here to minimise any residual resistance.

Using the thinner insulated wire, solder the wires from the LCD display, the buzzer and the battery compartment to the remaining veropins on the underside of the main-board. The flying lead wires in
Figure 4 are shown coming out of top of board for clarity, but in actuality are connected to the bottom of the board via veropins as illustrated in Photo 2.

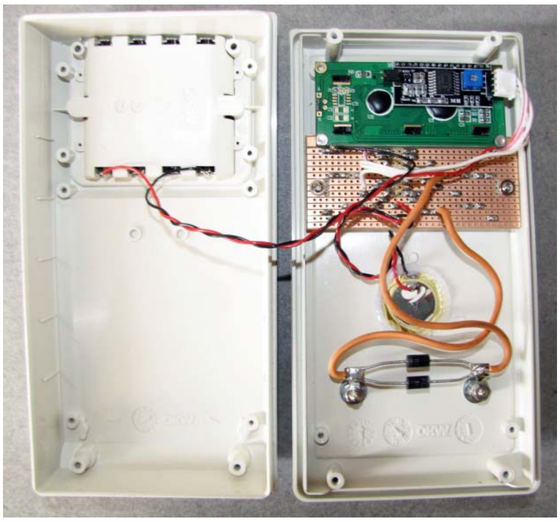


Photo 2 - Mounting components in the DATEC-MOBIL-BOX enclosure

Screw the front enclosure section to the back enclosure section. Insert 4 AA batteries. The meter should now be complete and ready for use.

Refer to the "ESR Meter Operating Guide" in the above section prior to use.

Happy testing!

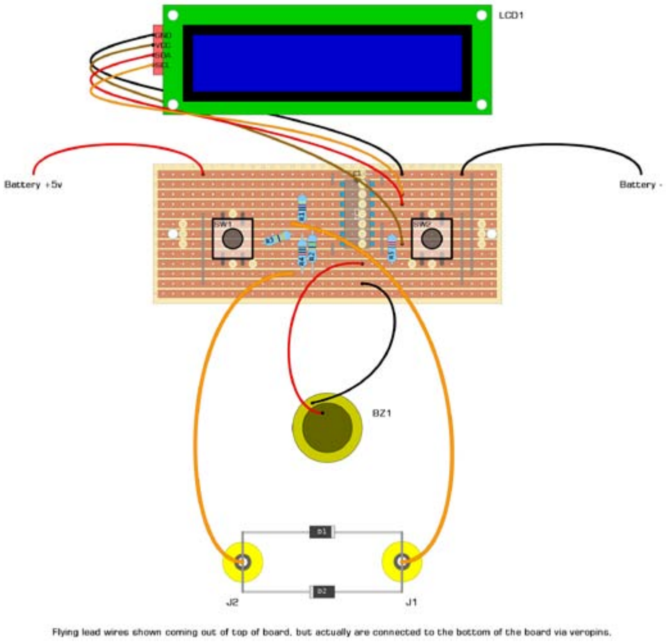


Figure 4 - Wiring components to the main-board

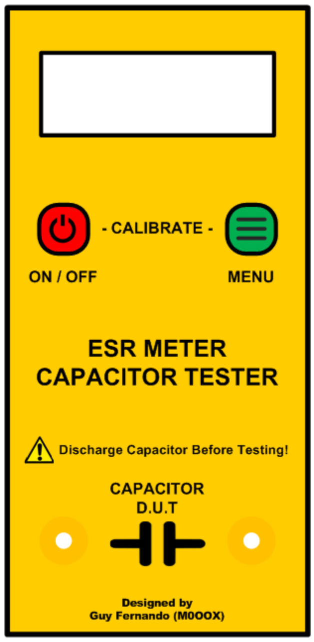


Figure 5 - Front panel artwork (80mm x 167mm)

Technical Specification

The specification quoted here based on the author's meter measured at 20°C with a 5.0v battery supply voltage. Values may vary depending on component tolerances and the construction method used.

Parameter	Minimum	Typical	Maximum
Capacitance measurement range	0.1µF	-	100,000µF
Capacitance accuracy	-	±5%	-
Capacitance resolution	-	3 significant figures ≥ 10.0µF	-
ESR measurement range	0.01Ω	-	50Ω
ESR accuracy	-	±5%	-
ESR resolution	-	3 significant figures ≥ 1.00Ω	-
Peak to peak testing voltage	-	150mV	-
Operating voltage range	4.6v	5.0v	5.6v
Operating current	-	20mA	-
Standby current	-	15µA	-
Flash memory write cycles		20,000	