Application Report
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Understanding MSP430 Flash Data Retention

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MSP430 Applications

ABSTRACT

The MSP430 family of microcontrollers, as part of its broad portfolio, offers both read-only memory (ROM)-based and flash-based devices. Understanding the MSP430 flash is extremely important for efficient, robust, and reliable system design. Data retention is one of the key aspects to flash reliability. In this application report, data retention for the MSP430 flash is discussed in detail and the effect of temperature is given primary importance. The concepts discussed in this document are applicable to all MSP430 devices that are flash based (F version), in any memory configuration.

1 Introduction

Memory in general is broadly classified as read-only memory (ROM) or random-access memory (RAM). These two types behave differently, and each has its own set of merits and demerits. Flash memory is a hybrid of ROM and RAM, inheriting the best features of both types of memories. Flash memory, driven by low cost, is electrically programmable, fast to read from, exhibits high density, and is nonvolatile. Flash memory is usually stacked as sectors and can be erased only as sectors. For the MSP430 devices, each sector of the main memory flash is 512 bytes in length. Because the flash memory is electrically programmable, it requires a sufficient voltage to erase and program efficiently. This voltage must be maintained during the entire flash erase/write to ensure reliability of the operation. This topic is discussed in detail in the following section. The other limitation of flash is the number of writes/erases, which has a direct impact on flash wear out. Tips to ensure flash longevity and factors that contribute to flash failure are discussed in this application report.

Data retention can be one of the primary concerns at extreme temperatures. In this application report, emphasis is given to basics of flash data retention, factors that influence this parameter, and the various figures of merit to interpret flash data retention, along with tips to prevent failures on the MSP430.

2 MSP430 Flash Characteristics

The *thick-oxide split-gate* cell design used in the MSP430 has several advantages in terms of data retention and endurance performance compared to other flash cell architectures such as *thin-oxide stacked-gate* or *thin-oxide two-transistor* cell designs. It is easier to manufacture and less susceptible than thin-oxide designs to manufacturing defects that relate to data retention loss over time.

2.1 Flash Programming

The erase state of every bit in any location in the MSP430 flash is logic 1. It is important and recommended that the user perform an erase operation before writing/programming is done to any location in MSP430 flash. Most of the MSP430 devices shipped from the factory have their main memory completely erased, while information memory might contain factory test data.

2.1.1 Programming Tips

In this section, a few external and internal tips that should be followed to minimize adverse effects during system design are listed. Failure to adhere to any of these tips may result in unreliable flash write/erase, leading to unpredictable flash behavior.

Internal Considerations

Efficient programming of the MSP430 flash is governed by two major requirements: supply voltage (DV_{CC}) and the flash timing generator clock (f_{FTG}). For the MSP430F1xx and most of the MSP430F4xx family of devices, the supply voltage must be a minimum of 2.7 V. The minimum supply voltage is reduced to 2.2 V and 1.8 V for the MSP430F2xx family and MSP430F5xx families, respectively. Particularly in battery-powered applications, battery capacity must be sufficient to meet the minimum operating voltage and currents necessary for in-application program/erase. The f_{FTG} for MSP430F1xx, MSP430F2xx, and MSP430F4xx devices must be in the range of $257\text{ kHz} \leq f_{FTG} \leq 476\text{ kHz}$, while it is generated internally on the MSP430F5xx devices. There is a practical limit on the number of flash erase/write cycles for every MSP430, which is in the range of 100,000 cycles.

External Considerations

Use of a programming adapter that has been certified to meet the MSP430 flash programming specifications greatly reduces the risk of a flash failure. Regular inspection for wear out of the programming socket also ensures better performance over time. If in-circuit programming is done via JTAG or boot loader, the programming operation should be performed at the end of the manufacturing cycle. Mechanical and thermal process steps, such as encapsulation mold cure, should be completed before programming.

Verification is an important step that can be implemented, if flash integrity must be checked. A checksum routine can be called on a regular basis for critical applications. In some of the MSP430F2xx, MSP430F4xx, and MSP430F5xx devices, the Marginal Read Mode is implemented to facilitate a checksum routine. Checksum routine values with and without this feature are compared to find weak programming flash locations on the MSP430. Different values may indicate a violation of one or more of the above mentioned programming considerations.

2.2 Flash Failure Mechanism

This section describes a few intrinsic and extrinsic failure mechanisms of flash memory. Although these mechanisms are applicable to any industry flash, they apply to the MSP430 flash as well. Several tests are in place to ensure that each MSP430 that leaves the factory does not show any of the following symptoms.

Charge Retention

Charge retention is the ability of the flash cell to retain its programmed value during long-term storage. If there are defects in the dielectrics or the substrate, charges can move to or from the floating gate, causing elevated charge loss. Also, with sufficient thermal activation, all bits could lose their charge. Analyses indicate that this failure mechanism occurs well beyond the normal lifetime of the device. Charge retention is discussed more in Section 2.3.

Oxide Degradation

The high fields used during program and erase can result in increased low field leakage through the dielectrics of the cell. This can increase the susceptibility to charge loss of the cell. Analyses and long-term storage results have verified that the post-cycling retention performance of the cells extends well beyond normal lifetimes.

Program/Erase Time Degradation

After a large number of write/erase cycles, a high charge can be trapped in the dielectrics surrounding the floating gate. This charge can decrease the effective field across the cell during program and erase operations, increasing the time required to complete the program/erase operations. Data on TI flash cells has shown that the erase/program time walk-out is well beyond normal use conditions.

Write Disturb

During the program operation, high fields are placed not only on the bit being programmed, but on other bits along the same word line and/or bit line. If there are defects in the dielectrics or in the substrate, leakage paths can be created, so inadvertent programming of a non-selected bit can be observed. To address this defect mechanism, high-voltage screens are in place in the test program to eliminate such units from the population.

These are some of the failure mechanisms that could occur to any flash, and tests are place to for screen out any MSP430 devices that might have them.

2.3 Flash Data Retention

Data retention of any flash is the ability to retain its programmed state. Flash data retention is known to degrade over temperature. Various tests and methods are in place to determine the reliability of flash. Tthis application report mainly addresses the concept of accelerated test and the use of statistics to predict reliability.

2.3.1 Accelerated Tests

To test the flash data retention at various temperatures we make use of accelerated tests on the flash. These tests are wholly based on Arrhenius law and equation. The Arrhenius theory allows the test of any device under accelerated environments for short periods and predicts the behavior under normal conditions for longer periods. Similar tests are performed on the MSP430 flash to test and predict data retention. During each test, an unprogrammed device is subjected to these tests. A flash failure is indicated when any of the flash cells change from an unprogrammed state (logic 1) to logic 0. The Arrhenius equation is shown in Equation 1.

$$AF=e^{-\frac{E_a}{k}\left(\frac{1}{T_2}-\frac{1}{T_1}\right)} \tag{1}$$

AF = Acceleration factor

E_a = Activation energy (0.6 eV for data retention)

k = Boltzmann's constant (8.623 x 10^{-5} eV/K)

T1 = Application junction temperature in Kelvin

T2 = Accelerated stress junction temperature in Kelvin

Depending on AF, a back calculation using the Arrhenius equation for any desired temperature leads to fairly accurate data-retention times.

Infant Mortality Test During Production

This test is not a flash data retention test, rather, it is performed to screen out infant mortality among devices during production. It is an accepted theory that all devices statistically follow a bathtub curve when it comes to failures. The infant mortality failures would fall into the left hand slope of the bath tub curve. Under this test, all of the MSP430 devices are baked for 72 hours or 144 hours at 250°C.

Flash Data Retention Tests During Qualification

To determine the flash data retention, further tests are conducted during qualification of the MSP430 devices. Two cases are explained in this section for different temperature and baking time.

Case 1: 420-Hour Baking Time at 170°C

In this test, the MSP430 is continuously subjected to this high temperature of 170°C for 420 hours. The purpose of this test is to determine data retention at higher temperatures, and then calculate expected data retention at 25°C using Equation 2.

Using T1 = 25°C and T2 = 170°C in Equation 1 gives the following AF:

$$AF=e^{\frac{-E_a}{k}\left(\frac{1}{(170C+273)}-\frac{1}{(25C+273)}\right)}=e^{\frac{-0.6}{8.623\times10^{-5}}\left(\frac{1}{(443)}-\frac{1}{(298)}\right)}=2085 \tag{2}$$

Using this AF information, back substitution gives the data retention in years at 25°C.

$$\text{Data\_retention}_{\text{years@25C}} = \frac{420 \times 2085}{24 \times 365} \approx 100\text{years}$$

After this value has been established, different AF values can be calculated for different T2 temperatures. Similar back substitution yields data retention in years. Figure 1 shows the data retention versus temperature for this test.

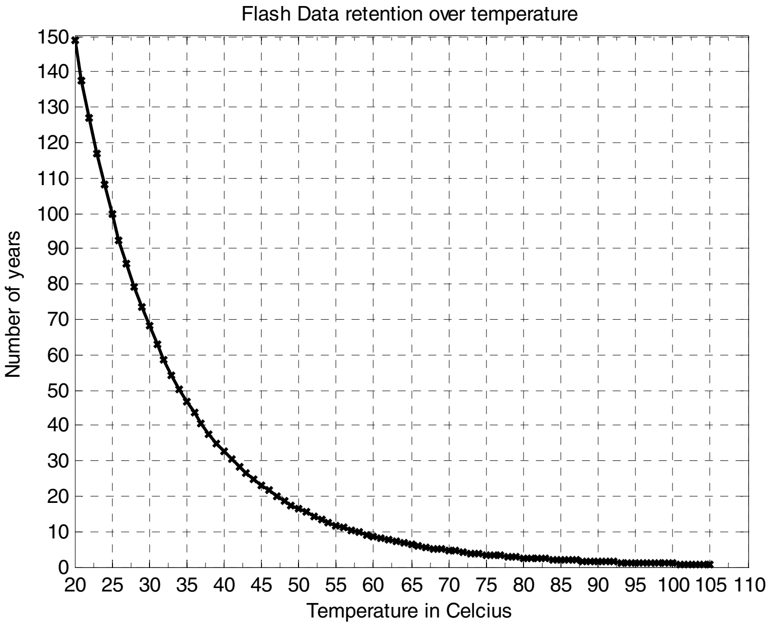

Figure 1: Flash Data Retention vs Temperature for 170°C 420-Hour Test

The corner cases for 85°C and 105°C are slightly over 2 years and less than 9 months, respectively. These numbers do not truly indicate the performance of the MSP430 flash. To qualify the MSP430 to have better data retention, further tests are conducted on the MSP430 flash.

There are instances in which there are strict requirements for flash data retention, particularly when the device is subjected to extreme temperatures. Although, in almost all cases, the device would never be subject to extreme temperatures 24 hours a day, 7 days a week, tests are in place to achieve better numbers at the corner case temperatures. To improve data retention for corner case temperatures, bake time must be increased. One such approach is to fix the bake temperature and use Equation 1 to establish bake time for the requirements on data retention. The bake temperature has been increased from case 1 to a temperature of 250°C. This test is performed on the flash used in the MSP430.

Case 2: 500-Hours Baking Time at 250°C

Putting these parameters into Equation 1, the AF is calculated as shown in Equation 3.

$$AF = e^{\frac{-E_a}{k}\left(\frac{1}{(250C+273)}-\frac{1}{(25C+273)}\right)} = e^{\frac{-0.6}{8.623\times10^{-5}}\left(\frac{1}{(523)}-\frac{1}{(298)}\right)} = 23044 \tag{3}$$

This value indicates the huge effect baking temperature has on flash data retention. The AF is almost ten times higher, implying that the data retention numbers would significantly improve.

Similarly, data retention at 25°C is calculated in Equation 4.

$$\text{Data\_retention}_{\text{years@25°C}} = \frac{500\times23044}{24\times365} \approx 1315 \text{ years} \tag{4}$$

Figure 2 shows the data retention versus temperature.

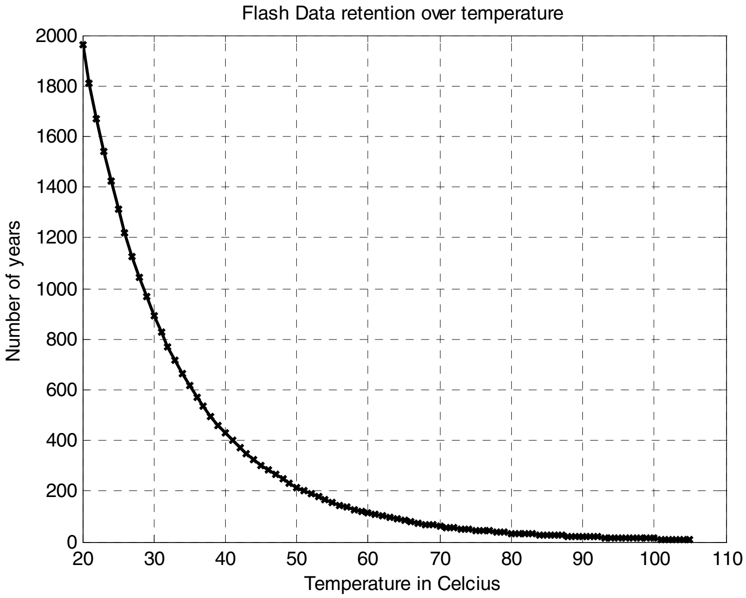

Figure 2: Bake Time and Temperature Increased to 500 Hours at 250°C

This data qualifies the device to almost 10 years at the extreme temperature of 105°C and nearly 27 years at 85°C.

Cases 1 and 2 discussed one method of interpretation of flash data retention. In the next section, the statistical measure of flash data retention is discussed. Appendix A lists the values charted in Figure 1 and Figure 2.

2.3.2 Reliability Tests

In general, reliability is defined as the probability that a device or a system will perform a required task under stated conditions for a stated period of time. The chosen functionality under specific conditions can be predicted with a good degree of confidence with this measure. For the present subject, the functionality is flash data retention, and the conditions are changes in temperature. In general, failure in devices follows a bathtub curve shown in Figure 3. The curve can be divided into three regions of interest: infant mortality, normal life of operation, and wear-out phase. The chances of failures are higher during infant mortality and the wear-out phase and almost a negligible constant during normal life of operation. In the previous section, screening out devices that fall under the infant mortality part of the curve was mentioned.

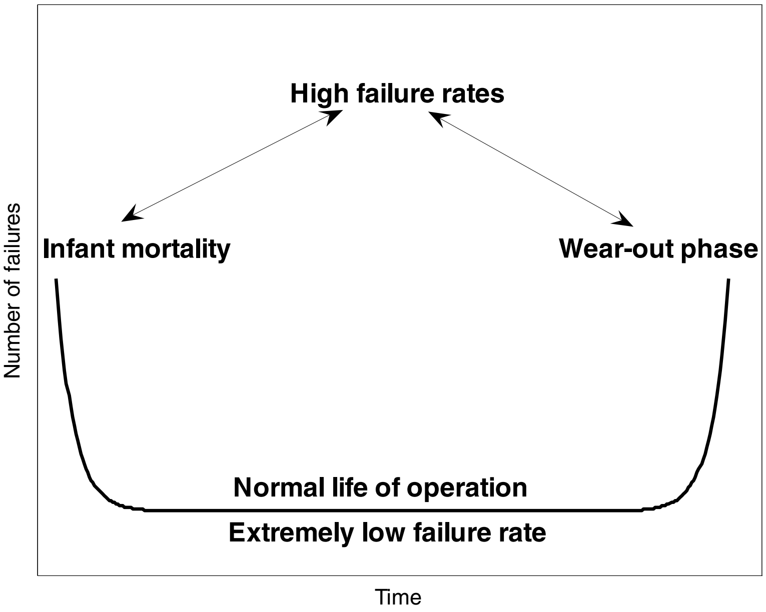

Figure 3: Bathtub Curve for Failures

The interpretation of test results to indicate the reliability of a device requires the definition and understanding of a few key parameters. A brief introduction to these terminologies follows:

Failure Rate (λ)

Failure rate is the number of failures per unit time. It follows the bathtub curve of Figure 3.

Failure-In-Time (FIT) Rate

FIT is a direct measure of failure rate in 10^9 device hours or the number of devices that failed after 10^9 hours. It is inversely proportional to number of devices tested and the duration of the tests.

Acceleration Factor (AF)

AF is an outcome of an accelerated life test done on the device to predict its long-term performance. Its role in the Arrhenius equation was shown in previous sections. This factor also contributes inversely to the FIT.

Confidence Level (CL)

CL is the probability level estimated based on sample tests conducted for failures. It also is a confidence in the integrity of numbers used to determine the failure rate. It follows a chi-square (χ^2) distribution and depends on the number of failures. In most cases, the confidence level is chosen to be 60% or 90%. It directly contributes to the FIT.

Mean Time Between Failures (MTBF)

MTBF is the inverse of the FIT for a repairable device and is a classic measure of reliability of a system or of a product. It is figure that goes through constant update with number of samples tested and failed.

Reliability [R(t)]

R(t) is defined for fixed time periods to predict the number of devices that would perform reliably. It is a byproduct of the FIT and expressed as a percentage.

From this point on, it is a simple task of putting these numbers in their respective formulae to get reliability data. An example is shown for the tests discussed in the previous section.

Example 1

Consider the test conducted in Case 1 for MSP430 flash with the temperature set to 170°C for a time of 420 hours. The sample size is 240 and the AF, FIT, and MTBF are shown for confidence levels of 60% and 90%.

The AF is still calculated using Equation 1 for each temperature in question:

$$AF = e^{\frac{-E_a}{k}\left(\frac{1}{(170C+273)}-\frac{1}{(30C+273)}\right)} = e^{\frac{-0.6}{8.623\times10^{-5}}\left(\frac{1}{(443)}-\frac{1}{(303)}\right)} = 1418$$

H = Time for which the device is tested for in hours = 420

N = Number of devices = 240

$$FIT = \frac{\left({}^{X^2}\!/_{2}\right)\times10^9}{N\times H\times AF}$$

The value of $\chi^2/2$ for confidence levels of 0.6 and 0.9 from the χ^2 distribution gives a value of 0.916 and 2.305 respectively. The FIT is therefore:

$$FIT_{30^0C,0.6CL} = \frac{\left(\chi^2 \big/ 2\right) \times 10^9}{N \times H \times AF} = \frac{(0.916) \times 10^9}{240 \times 420 \times 1418} = 6.41$$

$$FIT_{30^0C,0.9CL} = \frac{\left(\chi^2 \big/ 2\right) \times 10^9}{N \times H \times AF} = \frac{(2.305) \times 10^9}{240 \times 420 \times 1418} = 16.13$$

The FIT numbers are expressed in number of parts failing per billion units, as indicated by the 10^9 factor.

Once the FIT numbers are known, it is easy to calculate the MTBF defined by:

$$MTBF_{years} = \frac{1}{FIT \times 24 \times 365} \times 10^9$$

$$MTBF_{years,30^0C,0.6CL} = \frac{1}{FIT_{30^0C,0.6CL} \times 24 \times 365} \times 10^9 = \frac{1}{6.41 \times 24 \times 365} \times 10^9 = 17809\,years$$

$$MTBF_{years,30^0C,0.9CL} = \frac{1}{FIT_{30^0C,0.9CL} \times 24 \times 365} \times 10^9 = \frac{1}{16.13 \times 24 \times 365} \times 10^9 = 7077\,years$$

Example 2

If the reliability for a fixed period of time needs to be calculated for a device, the following equation can be used:

$$R(t) = e^{-t/MTBF}$$

t = Period of interest

In combination with Example 1, a problem statement can be derived to determine the reliability of a device that is constantly subjected to a single temperature for a set period of time. Suppose t is defined as 20 years and the MTBF for 30°C was used (from Example 1) with confidence levels of 0.6 and 0.9, the reliability is:

$$R_{30^\circ C,0.6CL}(t) = e^{-t/MTBF} = e^{-(20/17809)} = 0.9988 = 99.88\%$$

$$R_{30^\circ C,0.9CL}(t) = e^{-t/MTBF} = e^{-(20/7077)} = 0.9971 = 99.71\%$$

These results indicate the reliability of the MSP430 flash data retention devices at a fixed temperature and time. If Case 2 results were used in Example 1 and Example 2, the numbers obtained for MTBF and reliability would be even better.

3 Conclusion

This application report has addressed the means to understand data retention for the MSP430 flash. Various tests performed on the MSP430 that truly reflected flash data retention in number of years were described. Statistical measures were introduced to understand the MSP430 performance. Examples showed how MTBF numbers can be used to calculate reliability of an MSP430 under various conditions influenced by temperature.

Appendix A. Tabular Results

Case 1 Results

Temperature (°C)	Data Retention (Years)
20	148.912
25	100.000
30	68.006
35	46.843
40	32.652
45	23.020
50	16.406
55	11.814
60	8.591
65	6.307
70	4.672
75	3.491
80	2.630
85	1.997
90	1.528
95	1.178
100	0.914
105	0.714

Case 2 Results

Temperature (°C)	Data Retention (Years)
20	1959.187
25	1315.313
30	894.733
35	616.298
40	429.597
45	302.872
50	215.853
55	155.432
60	113.033
65	82.979
70	61.466
75	45.926
80	34.599
85	26.272
90	20.102
95	15.493
100	12.024
105	9.395

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