White Paper

WP22-1120-01

Impact of Temperature on SSD Data Retention

Introduction

When targeting longevity and reliability, it is necessary to consider how temperature affects an SSD's ability to store and retain data. At higher temperature, the NAND experiences greater acceleration of "charge detrapping" that could lead to random data bit failures. This paper describes how temperature impacts NAND data retention.

Detrapping of Stored Charge

See Figure 1 below. In the floating-gate transistor, an insulating oxide layer resides between the floating gate and the substrate. During program/erase (P/E) operations, tunnel current passes through the oxide layer of the floating gate in the NAND cell.

This occurrence, known as electrontunneling causes the buildup of charge traps in the tunnel oxide layer. These traps eventually accumulate to the point where the tunnel oxide becomes conductive without applying an input voltage, and the cell can no longer store charge.

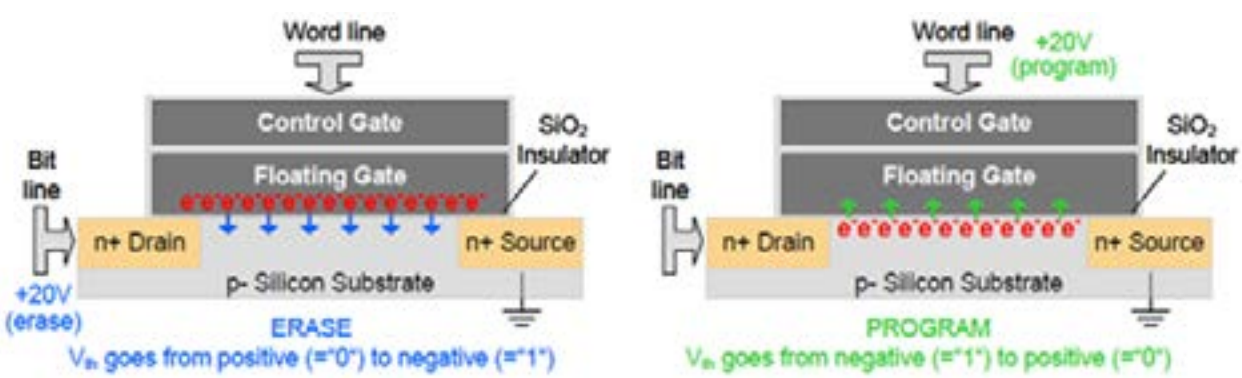


Figure 1: The Floating-gate Transistor

They may also inhibit normal programming of the NAND cell, which in turn affect its performance and or increases the write amplification factor resulting in reduced endurance.

Depending on the wear stage of the oxide layer, detrapping may occur immediately after the NAND cell is programmed. This causes a lower threshold voltage as intended by the NAND program algorithm which leads to a potential reading error.

Detrapping of stored charge occurs naturally over time and is further accelerated with the exposure to high temperature, which is the limiting factor in NAND data retention. The rate of reaction for a given temperature can be described by the Arrhenius equation, and the activation energy can be used to calculate the acceleration of charge detrapping in the NAND cell.

Arrhenius Equation:

$$k = Ae^{-\frac{E_a}{RT}}$$

Where: `

k = rate constant

T= temperature in Kelvin

A= accelerating kinetic factor

Ea= activation energy

R= Boltzmann constant

Ea for NAND according to JESD22-A117B is ~1.1eV, R = 8.617*10^-5 eV/°K, therefore the calculated k = 12765. The ratio of the two rates of reaction will equal the accelerating factor:

Equation 2:

$$Acclerating\ Factor = \frac{exp(\frac{Ea}{kT2})}{exp(\frac{Ea}{kT1})} = \mathrm{Exp}[(-k(\frac{1}{T2} - \frac{1}{T1})]$$

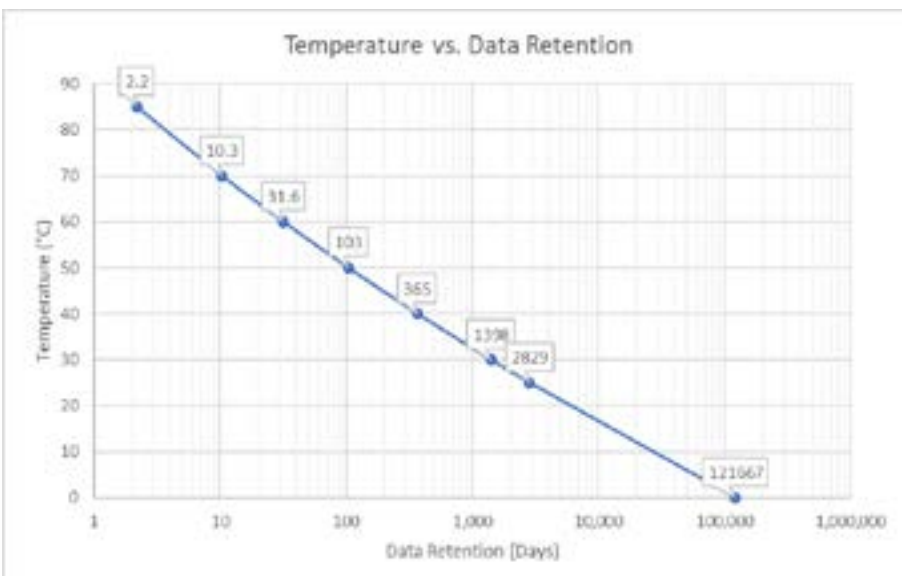
The acceleration factor for a NAND relative to a temperature of 40°C is shown in the Table . For example, if we take the manufacturer's specification for NAND devices specified with one year of data retention, storing the SSD at 50°C will accelerate the charge detrapping mechanism by 3.5

times when compared to storing at 40°C. The result is 103 days compared to 365 days at 40°C. Chart 1 provides an overview of temperature vs. data retention in days.

Table 1: Acceleration Factor vs. Storage Temperature

Storage Temp (°C)	Accerating Factor Relative to 40°C	Storage Duration (Days) @ End of Drive Life
85	167.6	2.2
70	35.3	10.3
60	11.6	31.6
50	3.5	103
40	1.0	365
30	0.26	1398
25	0.129	2829
0	0.003	121667

Chart 1: Temperature vs. Data Retention (Days)

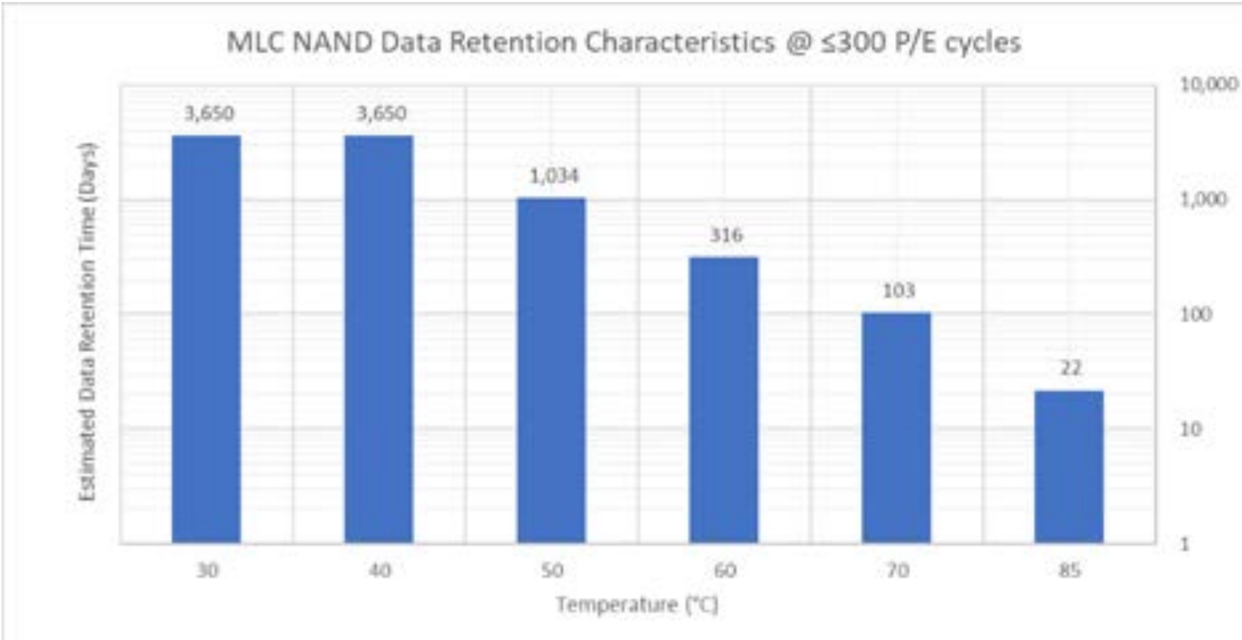


The calculations and discussions above describe the data retention towards the end of life for the SSD. SSD in its early stage is significantly higher. Manufacturers typically guarantee their NAND will store data for at least 10 years up to the first ~10% percent of use, stored at 40°C.

Therefore, an SLC NAND (if rated 100K P/E cycles) could go through 10K P/E cycles stored at 40°C, and its data retention is expected to last 10 years, while NAND with 3K P/E cycles is limited to the first 300 P/E cycles.

Applying the Arrhenius equation, the estimated data retention across various storage temperature is shown in the Chart 2. Note that the graph shows 10 years at 30°C, when in reality it is close to 40 years (13985 days) if we extend the Arrhenius Equation.

Chart 2: Data Retention Characteristics



Cross Temperature Operation

The warranty discussed did not mention the exact operating temperature. NAND manufacturers knows that operations typically take place in the warmer environment and conditions. Operations may occur in the cold only for a few minutes or so. After a while, electronics including the NAND chips will warm up due to heat dissipation.

However, it is important to note that writing operations in the cooler temperature is more detrimental than it is in the warmer temperature. Writing in the cooler temperature requires more energy for electrons to tunnel through the oxide layer.

This in turn significantly causes more damage to the oxide layer compared to writing operations in the warmer temperature. Conversely, reading at a higher temperature takes more energy and precision compared to reading in the cooler temperature, since electrons are more likely to lose its charge in the warmer temperature. Analogously, this is similar to playing on the ice formed on the surface of the lake in the middle and toward the end of winter. You are more likely to fall in the lake when it is warm.

Exact knowledge of the impact of data retention at various temperatures is difficult and requires an immense amount of time to test and verify. Furthermore, there are just too many variables to consider.

NAND manufacturers set a standard operating temperature of (0°C to 70°C) for commercial-temp SSD and (-40°C to 85°C) for industrial-temp SSD with data retention of one year at end of life and 10 years up to 10% of use stored at 40°C.

Data retention for storage temperature outside the specified range can be extrapolated using the Arrhenius Equation. Table 2 from Intel provides an overview of how data retention in days (blue columns) relate to temperature.

Table 2: Comparing power-off storage temperature vs. various operating temperatures.

Power Off Storage Temperature	25°C	30°C	35°C	40°C	45°C	50°C	55°C
55°C							56
50°C						56	103
45°C					56	112	192
40°C				84	112	196	365
35°C			84	140	448	392	200
30°C		112	168	280	448	784	1398
25°C	196	252	336	560	924	1624	2829
	Operating Temperature						

In this example, a one-year data retention is assumed with exact operating temperature of 55°C and storage temperature at 40°C. If the SSD was operating at 55°C, but stored at 30°C, its data retention is expected to extend to no less than ~1398 days. However, had it been operating and stored at 30°C, that number drops to about 112 days.

It is apparent, in terms of data retention that the best condition to operate the SSD would be in the high temperature range and store it in a cold environment.

Conclusion

NAND reliability is limited by the program/erase operations that over repeated use degrades the tunnel oxide layer. This in turns causes series of issues affecting endurance, performance, read accuracy and data retention.

It should be noted that at the end of the NAND's rated life, the NAND device is not in jeopardy of immediate failure. NAND manufacturer's endurance ratings are typically specified to ensure that the number of bad blocks that occur over time will be within a predictable percentage limit and that the NAND will be able to retain data for one year at 40°C.

Over time, NAND cells may lose enough charge and flip enough bits and overwhelm the ECC capability of the SSD controller and cause data loss. The best way to optimize data retention of an SSD is to limit its exposure time to high temperature at which it is stored.

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