Mathematical Modeling of NAND Flash Retention Times for Quick Spreadsheet Calculations

Technical Article

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In the industrial segment, particularly in the Automotive and Aerospace sub-segments, a great deal of emphasis is placed on system reliability.

For systems that include storage media based on NAND flash memory (which is almost all of them), one of the most critical parameters for overall system reliability is data retention time. This is defined as the maximum time that data can be stored reliably, after which, the data read from a NAND generates a Raw Bit Error Rate (RBER), exceeding the correction limits of the adopted error correction code (ECC) algorithm and resulting in data loss or corruption that can compromise system operation and safety.

Given the extreme conditions under which storage media must operate, accurately estimating this parameter is sometimes essential, taking into account the specific operating environment. It is common knowledge that the data retention time depends exponentially on temperature, as well as on wear, which is defined by the number of Program/Erase cycles the NAND has undergone. Consequently, an estimation may be necessary based on the temperatures to which the device has been exposed, particularly when the storage media is approaching its wear limit and operates in environments with significant temperature fluctuations. This highlights the practical importance, especially for system manufacturers, of having methods that are both straightforward and sufficiently accurate. This article aims to provide a mathematical model that describes, with sufficient accuracy, the dependence of data retention time on temperature and wear.

A Simplified Analytical Model for Retention Time

In NAND memory technology, it is common practice to express retention time as the product of two component functions, one modeling its dependence on temperature and the other on wear, as analytically described in the following equation.

$$t_r(N,T) = t_r\left(0, T_{ref}\right)\, g(N)\, AF(T_{ref}, T) \qquad \text{Eq. 1}$$

Where:

- N is the number of Program/Erase cycles.
- T is the temperature in Kelvin.
- $t_r(N,T)$ is the calculated Retention Time at N and T.
- T_{ref} is the reference temperature, where $t_r\left(0, T_{ref}\right)$ is known.

- $t_r(0, T_{ref})$ denotes the retention time at N=0 and T=T_{ref}; this is a constant, technology-dependent parameter.
- $g(N)$ is the envelope function of N applied to $t_r(0, T_{ref})$, with codomain [0;1].
- $AF(T_{ref}, T) = \left[e^{-\frac{E_a}{k}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)} \right]$ is the well-known Arrhenius acceleration factor, modeling the effect of temperature on $t_r(N, T)$. Further details on $AF(T_{ref}, T)$ are provided in appendix B.

The function g(N) warrants, instead, a dedicated discussion, provided in Appendix A, as it strongly influences the overall accuracy of the model. We therefore encourage the interested reader to consult Appendix A for a deeper examination of the applicability of the function below, which has been chosen in this simplified model.

$$g(N) = e^{-\frac{N}{\nu}} \qquad \text{Eq. 2}$$

Where:

- ν is a NAND process-dependent parameter.

Thus, the complete model can be expressed as:

$$t_r(N, T) = t_r(0, T_{ref})\ e^{-\frac{N}{\nu}} \left[e^{-\frac{E_a}{k}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)} \right] \qquad \text{Eq. 3}$$

Let us now note that the quantity $g(N, T_{ref}) = t_r(0, T_{ref})\, g(N)$ represents the retention time as a function of *N* when $T = T_{ref}$. Once $g(N, T_{ref})$, which captures the dependence of $t_r(N, T)$ on *N*, has been determined, the additional dependence on temperature T is entirely accounted by the acceleration factor $AF(T_{ref}, T)$ described in Appendix B.
It is important to note that the proposed model assumes monotonicity of the wear-dependent function and independence between the effects of temperature and wear. In certain advanced technologies, such as 3D NAND Charge Trap, interactions between temperature and wear can emerge and may affect the estimation of retention time. Nonetheless, simplified models that assume independence between these effects can still provide useful approximations in many practical scenarios.

Model Fitting

From the above model, it is clear that its application requires the determination of parameters T_{ref}, ν and $t_r(0, T_{ref})$, since the remaining (E_a , k) are known physical constants (see Appendix B). Moreover, owing to the simplicity of $g(N, T_{ref})$, its fitting can be performed with as few as two data points and does not require complex numerical methods.

At this stage, the reader will naturally wonder where to obtain the data required to perform the fitting. Fortunately, NAND vendors typically provide such information, usually in the form of at least a couple of $[N\ ;\ t_r(N,T)\ ]$ data points at a given temperature, in a format like the one in the table below.

Storage Temperature: 55°C	
Wear (P/E cycling) [% of Maximum]	**Retention Time [Years]**
10%	5
90%	1

Table 1. Example of Retention/Wear data points provided by NAND manufacturer

It should be noted that, in Table 1, wear is expressed as a percentage relative to the maximum allowed value for the specific NAND technology, rather than in absolute values; however, this does not limit the applicability of the model.

Accordingly, the following definitions can be introduced:

$T_{ref} = 328.15\ K$ (in Celsius 55°C)
$N_1 = 10\%\ ,\ g_1\left(N_1, T_{ref}\right) = g_1 = 5y$
$N_2 = 90\%\ ,\ g_2\left(N_2, T_{ref}\right) = g_2 = 1y$

By straightforward algebraic manipulation, the following equations and values can be obtained:

$$\bar{\nu} = \frac{N_1 - N_2}{ln\left(\frac{g_2}{g_1}\right)} = \frac{0.1 - 0.9}{ln\left(\frac{1}{5}\right)} = 0.497 \qquad \text{Eq. 4}$$

$$\bar{t}_r\left(0, T_{ref}\right) = \frac{g_1}{e^{-\frac{N_1}{\bar{\nu}}}} = \frac{5}{0.818} = 6.11 \qquad \text{Eq. 5}$$

In conclusion, with the last set of equations the model parameters can be fully determined, provided that at least two data points $[N_i\ ;\ t_r(N_i,T)\ ]$ (i=1,2) are available. At this stage, the mathematical model can be readily implemented in a standard Excel spreadsheet. This can be achieved by assigning variable names to the input cells (via the 'Define Name' option under the 'Formulas' menu) and then calculating the target retention time in the output cell using the formula shown below (Eq. 6)."

NAND Process-Dependent Parameters			
N %	tr [Y]	Ref Temp. [K]	Ea
N_1	tr_1	T_ref	Ea
N_2	tr_2		

Target Values	
Target Temp. [K]	Target N%
T_targ	N_Targ

Table 2 Name assignment by cells

(tr_1/EXP(-N_1/((N_1-N_2)/LN(tr_2/tr_1))))*EXP(-N_targ/((N_1-N_2)/LN(tr_2/tr_1) Ea*(1/T_ref-1/T_targ)/(8.62*10^(-5))) Eq. 6

Then, filling the input cells with the numerical data, the spreadsheet will appear as shown below:

NAND Process-Dependent Parameters			
N %	tr [Y]	Ref Temp. [K]	Ea
10%	5	303.15	1.00
90%	1		

Target Values	
Target Temp. [K]	Target N%
298.15	50%

Calculated Retention Time
Retention time [Y] @ Ttarget, Ntarget
4.248115908

Table 3. Retention Time calculation spreadsheet example

Before concluding, it is important to highlight the limitations of the proposed model. Specifically:

- Choosing N_Targ values outside the interval [N_1, N_2] may reduce the accuracy of the calculated retention time, with the error increasing as the distance from the interval boundaries grows.
- The accuracy of the retention time calculated at a target temperature T_targ critically depends on the precision of the activation energy (Ea) value used. This aspect becomes particularly critical in state-of-the-art NAND Charge Trap processes, where the Activation Energy (Ea) may exhibit distinct constant values across different temperature ranges.

Appendix A: A Brief Review of the Most Common Mathematical Models for Retention Time vs. Wear

In the following, some of the most widely adopted mathematical models describing the dependence of retention time on wear will be briefly introduced.

Pure Exponential

$$g(N) = e^{-\frac{N}{\nu}}$$

$$g(N, T_{ref}) = t_r(0, T_{ref})\, e^{-\frac{N}{\nu}} \qquad \text{Eq. 7}$$

This model is widely adopted in the industry owing to its simplicity and robustness. As demonstrated above, uniquely determining all the parameters in Eq. 7 requires only two independent data points, $[\,g(N_1, T_{ref}), N_1]$, $[\,g(N_2, T_{ref}), N_2]$, since the function is monotonic and depends on only two parameters.

Power Law

$$g(N) = N^{-\nu}$$

$$g(N, T_{ref}) = t_r(0, T_{ref}) N^{-\nu} \qquad \text{Eq. 8}$$

Where:

ν : constant parameters related to the NAND process;

$t_r(0, T_{ref})$: Retention Time at N=0 and T=T_{ref};

0<N<1 is given as % with respect to the N_{max} (Maximum P/E cycles allowed).

Even in that case, uniquely determining all the parameters in Eq. 8 requires only two independent data points, $[\,g(N_1, T_{ref}), N_1]$ and $[\,g(N_2, T_{ref}), N_2]$, since the function is monotonic and depends on only two parameters.

Modified Logistic Model

$$g(N) = \frac{1}{1 + \left(\frac{N}{N_0}\right)^{\nu}}$$

$$g(N, T_{ref}) = t_r(0, T_{ref}) \frac{1}{1 + \left(\frac{N}{N_0}\right)^{\nu}} \qquad \text{Eq. 9}$$

Where:
ν : constant parameters related to the NAND process;
$t_r(0, T_{ref})$: Retention Time at N=0 and T=T_{ref};
N_0 : is the wear at retention time half-life;
$0<N<1$ is given as % respect to the N_{max} (Max P/E cycles allowed).

Since this function has three independent parameters, uniquely determining all of them in Eq. 9 requires three independent data points, namely: $[g(N_1, T_{ref}), N_1]$ ... $[\,g(N_3, T_{ref}), N_3]$.

This model is suitable for industrial applications to model the remaining life for predictive maintenance.

Appendix B: Arrhenius Equation

$$AF(T_{ref}, T) = e^{-\frac{E_a}{k}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)}$$

Where:

- $AF(T_{ref}, T)$ is the acceleration factor due to changes in temperature, between T and T_{ref};
- E_a is the apparent activation energy; in general, for old NAND 2D processes 1.00eV< E_a < 1.10eV, while for most recent 3D processes 0.70eV< E_a < 0.99eV; for the most recent Charge Trap processes 0.70eV< E_a < 0.9eV;
- k is Boltzmann's constant (8.62 × 10-5 eV/K).

Conclusion

Data retention time is a critical parameter for system reliability in industrial systems, particularly in the Automotive and Aerospace sub-segments.

When the maximum time interval for reading data is reached, generated raw bit errors exceed the correction limits of the ECC algorithm. This leads to data corruption, which compromises the integrity of the stored data.

As data retention time depends exponentially on temperature and on wear, it is important to make precise estimates based on those parameters.

For more information on calculating the data retention times of ATP NAND flash solutions, please contact an ATP Representative in your area.

References

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