



Limitations of Arrhenius Law in Data Retention Time Estimation

White Paper

Table of Contents

Disclaimer

Limitations of Arrhenius Law in Data Retention Time Estimation	1
1. Introduction	1
2. Failure of Single-Activation Arrhenius Model.....	1
3. Charge Loss Mechanisms	3
3.1 Lateral Transport.....	3
3.2 Direct Tunneling	3
3.3 Thermal Emission	3
4. Implications for Modeling and Testing	4
5. Conclusion	4
6. References.....	4

Disclaimer

ATP Electronics Taiwan Inc. and its affiliates (“ATP”) shall not be liable for any errors or omissions that may appear in this document, and ATP disclaims any responsibility for any consequences resulting from the usage of the information set forth herein. Moreover, ATP is not warranted and liable for using any ATP product in developing, or for incorporation into, any products or services used in applications or environments requiring failsafe performance, including but not limited to the usage in the operation of aircraft navigation or air traffic control, life support machines, surgically implanted devices, or other applications, devices or systems in which the failure of the ATP product could lead directly to death, personal injury, or severe physical or environmental damage.

The information set forth in this document is considered to be “Proprietary” and “Confidential” and owned by ATP. All information in this document is protected by copyright law and all rights are reserved. This document may not, in whole or in part, be copied, photocopied, reproduced, translated, or reduced to any electronic medium or machine-readable form without the prior written consent of ATP.

All information provided in this document is for reference only and the stated information, the terms and conditions will be subject to change at any time without notice. By reviewing or using the information contained in this document, the receiving party or the reader of this document understands and acknowledges that ATP will not be liable for any provided information, nor for any changes, errors or omissions, or the usage of the provided information.

© Copyright ATP all rights reserved.

Limitations of Arrhenius Law in Data Retention Time Estimation

By Ercole Rosario Di Iorio, Manager, EU FAE

1. Introduction

Traditional analysis of charge retention in memory devices often relies on the Arrhenius equation, which assumes a single activation energy governs the thermally activated leakage. However, experimental studies reveal that in certain Charge-Trap (CT) Flash (based on SANOS, SONOS or TANOS stack process technology) devices, retention deviates significantly from this simple model. This white paper explains why the Arrhenius law fails in these cases and highlights the multiple physical processes that govern charge loss across a range of temperatures.

Note:

The following are different dielectric structures used for charge storage.

SANOS: Silicon-Aluminum Oxide-Nitride-Oxide-Silicon structure uses Aluminum Oxide (Al_2O_3) as the blocking layer.

SONOS: Silicon-Oxide-Nitride-Oxide-Silicon structure uses Silicon Oxide (SiO_2) as the blocking layer.

TANOS: Titanium-Aluminum Oxide-Nitride-Oxide-Silicon structure uses a Titanium gate and Aluminum Oxide (Al_2O_3) as the blocking layer.

2. Failure of Single-Activation Arrhenius Model

Traditional model of charge retention time in memory devices often relies on the Arrhenius equation (below), which assumes the thermal emission as dominant charge loss mechanism:

$$\tau = \tau_0 \cdot \exp[-E_a / (k_B (1/T - 1/T_0))]]$$

where:

τ is the retention time

E_a is the activation energy

k_B is Boltzmann's constant

T is the absolute temperature

T_0 is a reference temperature

This predicts a straight line when plotting $\log(\tau)$ versus $1/T$. However, for devices such as CT-Flash (SANOS, SONOS, TANOS common stack processes), physical measures deviate from linearity, particularly when the flash cell Tunnel Oxide thickness is below 4 nm.

Some studies, indeed, based on accurate physical models, better clarify the reasons of this observed deviation by considering primary charge loss mechanisms, like the direct tunneling and the lateral transport. In particular, it emerged that the retention curve in the Arrhenius diagram ($\log \tau$ vs $1/k_B T$), simulated on thin (<4 nm) Tunnel Oxide processes, could have multiple regions and each of them can be fitted by a straight line, characterized by a specific activation energy, E_a .

At low temperatures (Region 3 in Figure 1), the electrons transport, at the Tunnel_Oxide-Substrate interface, dominates over the lateral electrons transport and the Thermal emission but the behavior goes back to a pure Arrhenius one after the charge depletion of this region.

At moderate temperatures (Region 2 in Figure 1), direct tunneling mechanism, which is temperature insensitive, dominates. Therefore, the retention curve slope (E_a dependent) decreases.

At high temperatures (Region 1 in Figure 1), the thermal emission and lateral transport are prevalent with respect to the direct tunneling charge loss and that explains an Arrhenius-like behavior.

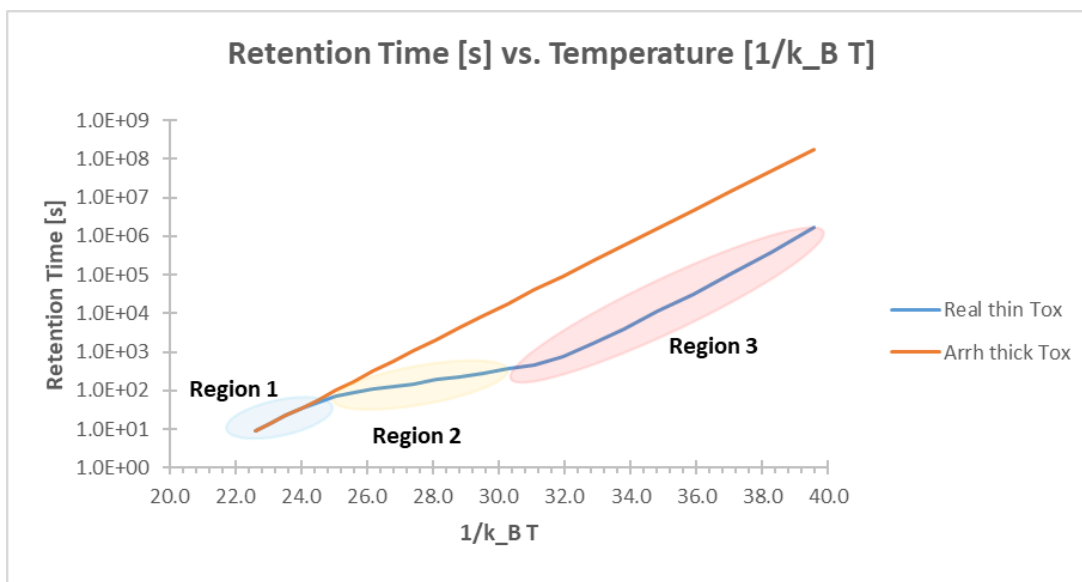


FIG. 1: Retention Time plot showing the traditional Arrhenius model and the simulated one, closer to the real phenomena, whose distinct slopes correspond to separate charge loss mechanisms.

3. Charge Loss Mechanisms

3.1 Lateral Transport

The Lateral Transport (white arrows in Figure 2) mechanism is mainly due to Poole-Frenkel effect, which is a thermally excited emission of electrons, from traps holding them in the Charge Trap Layer. This kind of transport is obviously temperature dependent.

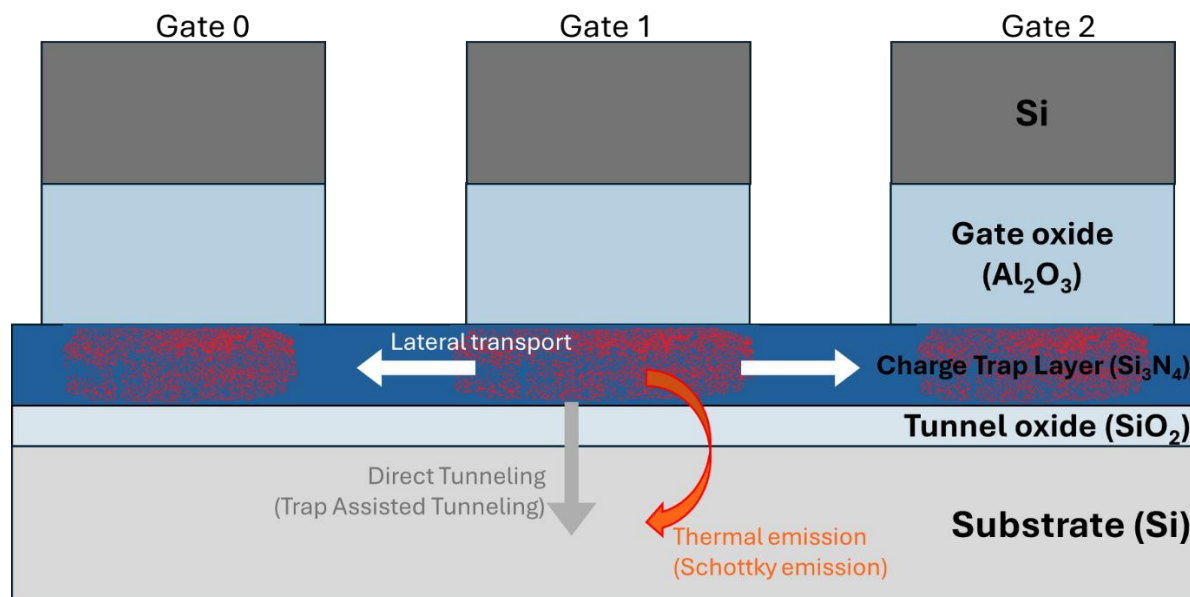


FIG. 2: Cross-section of a 2D CT memory cell showing key retention loss mechanisms.

3.2 Direct Tunneling

The Direct Tunneling (grey arrow in Figure 2) mechanism is mainly due to charge Trap-Assisted-Tunneling (TAT), which is the most famous tunneling mechanism. Since it does not require specific conditions, if traps are located in the Tunnel Oxide layer, then TAT takes place through the trap sites even at low electric field region. So, the electrons stored in Charge Trap layer can leak through the traps located in the Tunnel Oxide. This mechanism is temperature independent.

3.3 Thermal Emission

The major phenomenon contributing to the Thermal Emission (orange arrow in Figure 2) is the so-called Schottky Emission, which is a conduction mechanism taking place when electrons can get enough energy provided by thermal activation, so that they can

move to the Substrate by overcoming the energy barrier at the Charge Trap – Tunnel Oxide interface.

4. Implications for Modeling and Testing

Using a single activation energy extracted from high-temperature data would lead to erroneous predictions at normal operating temperatures. For example, fitting only the mid-temperature slope may significantly underestimate charge loss at high temperatures. Accurate modeling requires either piecewise Arrhenius fits for each regime or comprehensive physical simulations that capture all relevant mechanisms.

5. Conclusion

The Arrhenius law with a single activation energy is insufficient for accurately modeling data retention in leading edge CT-Flash and TANOS (SANOS, SONOS) devices. Multiple charge loss mechanisms, each with its own temperature dependence, lead to non-linear behavior in Arrhenius plots. Recognizing and incorporating these mechanisms ensures reliable data retention time predictions on SSD and NVMe based on the latest CT 3D NAND flash technologies.

6. References

1. Park, et al., “Investigation on multiple activation energy of retention in charge trapping memory using self-consistent simulation,” 2014.
2. Ji-Seok Lee and Ilgu Yun, “Analysis of mechanism about data retention characteristic in TANOS structures,” 2020.
3. R. Bez, et al., “Flash memory cells—An overview,” *Proceedings of the IEEE*, 2003.
4. J. Lee, et al., “Charge trapping behaviors and reliability in SONOS non-volatile memory,” *IEEE Transactions on Device and Materials Reliability*, 2002.