Limitations of Arrhenius Law in Data Retention Time Estimation

White Paper

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Limitations of Arrhenius Law in Data Retention Time Estimation

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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:

$$\tau = \tau_0 \; e^{-\frac{E_a}{k_B}\left(\frac{1}{T_0}-\frac{1}{T}\right)} \qquad \text{Eq. 1}$$

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(τ) 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 (lot τ vs 1/k_BT), 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, Ea.

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 (Ea 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.

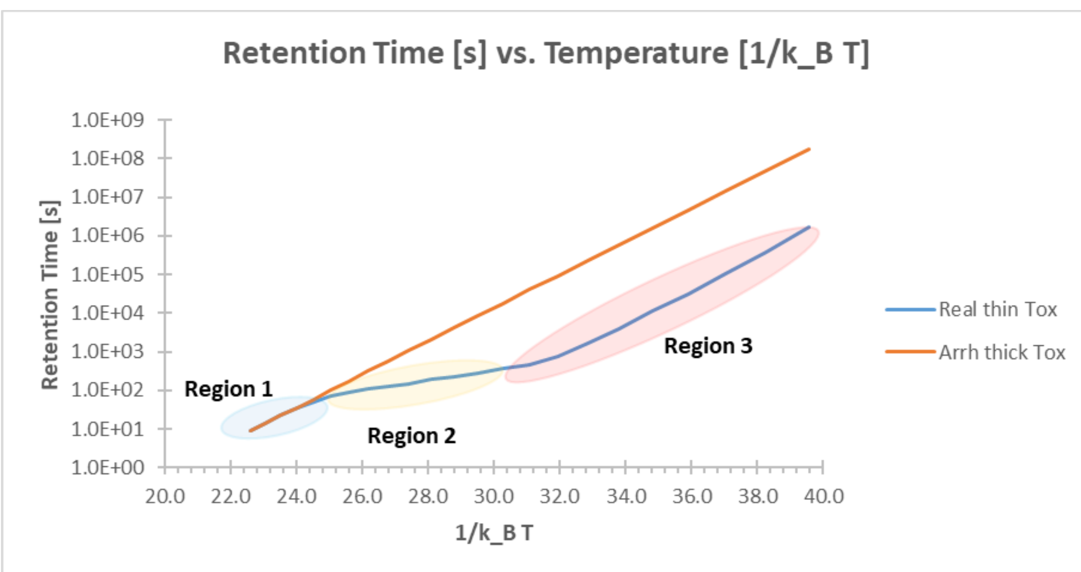

FIG. 1: Retention Time plot showing the traditional Arrhenius model and the simulated one, closer to the real phenomena, whose distinct slopes correspond to separate charge loss mechanisms.

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 exited emission of electrons, from traps holding them in the Charge Trap Layer. This kind of transport is obviously temperature dependent.

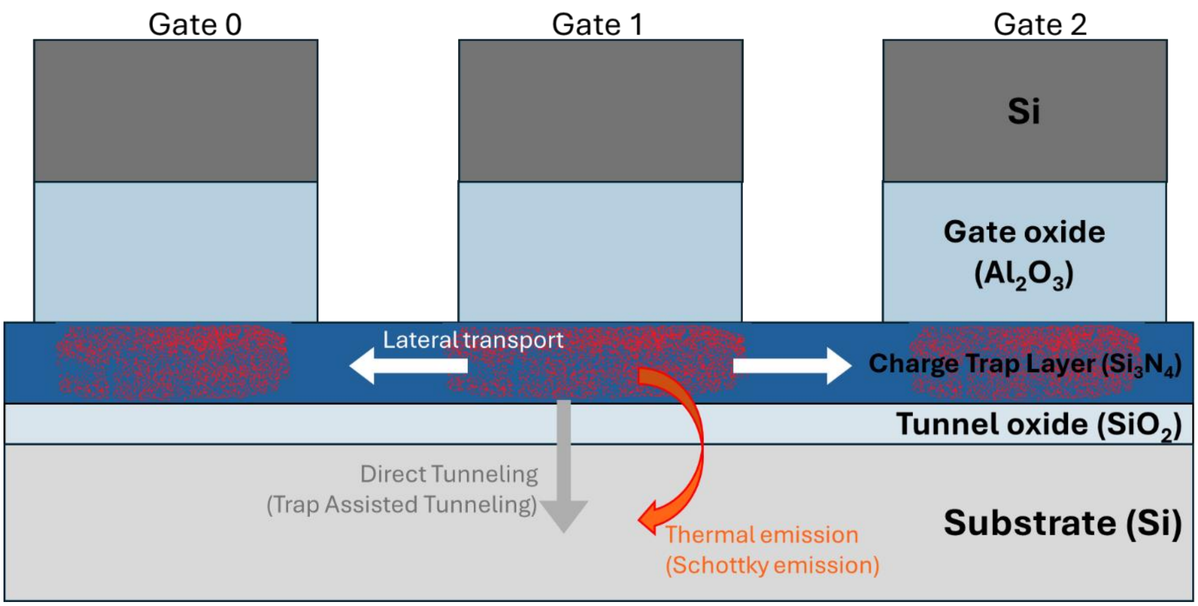

FIG. 2: Cross-section of a 2D CT memory cell showing key retention loss mechanisms.

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.

To further elaborate on the methodology used for fitting the retention time versus temperature curve, a preliminary step is required: extract the Activation Energy, referred as Ea(RT#), from each distinct linear region of measured data (FIG. 1 - Retention_Time vs. 1/kBT). Next, the transition temperatures between adjacent regions must be identified. These will be denoted as T_{Bi}, $T_{Bj.}$

Once these parameters have been established, it can be observed that the reference temperature T_0 and the operating temperature T may lie in different regions.

In particular:

1. If T_0 and T are in the same Region (i.e., Region 1) then Eq. 1 is still a valid model.

2. If T_0 and T are in adjacent regions (i.e., T_0 in Region 1 and T in Region 2), then the fitting equation will be:

$$\tau = \tau_0 \ e^{-\frac{1}{k_B}\left[E_a(R_T)\left(\frac{1}{T_{B_i}} - \frac{1}{T}\right) + E_a(R_{T_0})\left(\frac{1}{T_0} - \frac{1}{T_{B_i}}\right)\right]} \qquad \text{Eq. 2}$$

Where:

$\mathbf{E_a(R_T)}$ is the Activation Energy of the region where T lies

$\mathbf{E_a(R_{T_0})}$ is the Activation Energy of the region where T_0 lies

$\mathbf{T_{B_i}}$ is the boundary temperature between the adjacent regions where T_0, T lie

3. If T_0 and T are in extreme regions (i.e. T_0 in Region 1 and T in Region 3), then the fitting equation is a bit more complex:

$$\tau = \tau_0 \ e^{-\frac{1}{k_B}\left[E_a(R_T)\left(\frac{1}{T_{Bj}}-\frac{1}{T}\right)+E_a(R_2)\left(\frac{1}{T_{Bi}}-\frac{1}{T_{Bj}}\right)+E_a(R_{T_0})\left(\frac{1}{T_0}-\frac{1}{T_{Bi}}\right)\right]} \qquad \text{Eq. 3}$$

Where:

$\mathbf{E_a(R_2)}$ is the Activation Energy of Region 2 (central)
$\mathbf{T_{B_i}}$ is the boundary temperature between the region where T_0 is and Region 2
$\mathbf{T_{B_j}}$ is the boundary temperature between the region where T is and Region 2

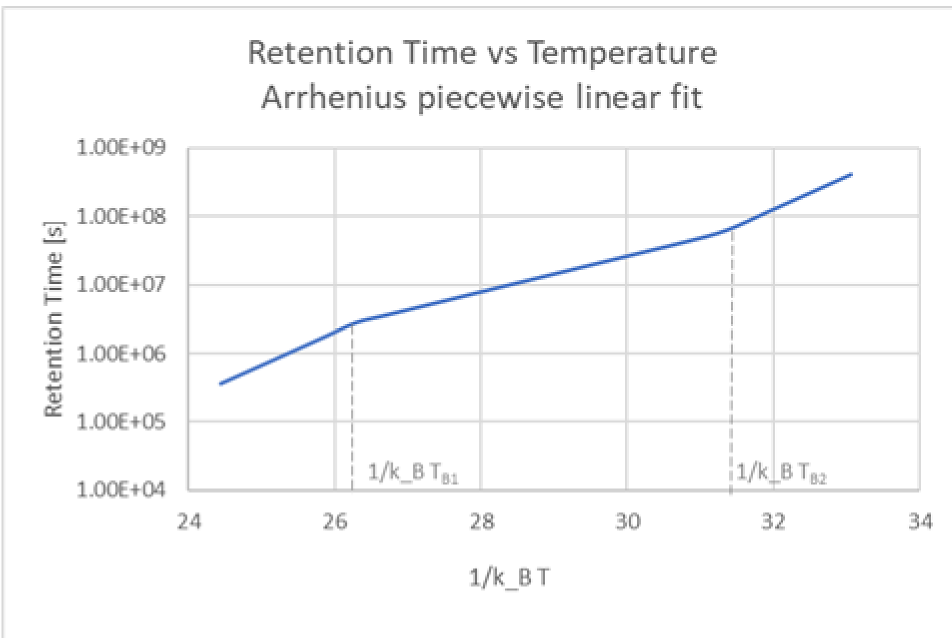

FIG. 3: Graph of piecewise linear fitting example.

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

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