Logarithmic behavior of the degradation dynamics of metal–oxide–semiconductor devices

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Abstract. In this paper the authors describe a simple theoretical statistical model of the process of relaxation in metal–oxide–semiconductor devices that governs the degradation. Basically, starting from an initial state where a given number of traps are occupied, the dynamics of the relaxation process is measured, and the density of occupied traps and its fluctuations (second moment) as a function of time are calculated. Our theoretical results show an emergent logarithmic behavior for the density of occupied traps: $\langle n(t) \rangle \sim \varphi(T, E_F)(A + B \ln t)$, i.e., the degradation is logarithmic and its amplitude depends only on the temperature and the Fermi level (applied bias voltage) of the device.

Keywords: interfaces in random media (theory), fluctuations (theory), current fluctuations
The understanding of the physics of semiconductor devices [1] has never been so important, since silicon-based integrated circuits are facing increasing reliability and scaling issues. Quantum computing [17], DNA computing [16], and many other alternatives are arising as possible substitutes for the technology of silicon-based computation, but these seem to be very distant from day-to-day reality.

Hence, the understanding of the reliability effects in semiconductors is of paramount importance for the microelectronics industry, which is more and more dependent of new results from interdisciplinary physics and their ramifications. Although the modeling approach presented here is simple, it is innovative and the results should be valuable in a very active research field and of great importance for the semiconductor industry.

Complementary metal–oxide–semiconductor devices (or simply CMOS devices) have an important role in the development of the information and electronics industry. A scheme for this device can be represented basically as in figure 2. As can be observed, it is composed of a thin metal plate, followed by an insulating layer (e.g., SiO$_2$), and finally a semiconductor layer (silicon—Si). The working of the device supposes two voltages:

(1) The gate–source voltage ($V_{GS}$), which controls the Fermi level of the charge carriers in the semiconductor, i.e., the electrons are attracted with larger or smaller intensity to the interface between the oxide and semiconductor according to the magnitude of $V_{GS}$.

(2) The drain–source voltage ($V_{DS}$), responsible for moving the electrons composing the current (the drain current). The uniformity of this current can be affected by charge traps found close to the semiconductor–insulator interface. In this context the rules of capture and emission of charge carriers by traps in semiconductor devices lead to irregular signals (noise) in the current which can be observed in figure 1.

In this figure we observe how the current of the device is affected by a single trap. The fluctuations observed experimentally are caused by the effect of the superposition of a number of traps under different conditions and, moreover, we can consider fluctuations from a sample of devices to completely describe these phenomena (see for example [4]).

Such fluctuations are called random telegraph signals [3]. In other contexts, for example in Ni/NiO/Co junctions [11], such fluctuations are even able to govern the magnetoresistance and their study will also be very important in the context of nanostructures (see for example [12,13]).

The capture and emission of charge carriers by the traps is described as a simple Poisson process governed by rates $\tau_c$ and $\tau_e$, where the capture occurs with probability $p(0 \to 1) \, dt = \tau_c^{-1} \, dt$ and the emission occurs with probability $p(1 \to 0) \, dt = \tau_e^{-1} \, dt$.

Such rates, $\tau_c$ and $\tau_e$, can be defined as the time averages in state 1 and state 0 respectively: $\tau_c = \langle t \rangle_1 = \int_0^\infty t P_1(t) \, dt$ and $\tau_e = \langle t \rangle_0 = \int_0^\infty t P_0(t) \, dt$, where $P_1(t)$ is the probability of permanency in state 1 and $P_0(t)$ the respective value for state 0. Naturally $P_1(t) = 1/\tau_c \cdot \exp(-t/\tau_c)$ and $P_0(t) = 1/\tau_e \cdot \exp(-t/\tau_e)$.

If the number of trapped charge carriers increases over time, a decrease of the current may be observed. This is an ageing effect usually called bias temperature instability (n-bti or p-bti), since it depends on the bias (Fermi level) and temperature, as discussed below.

In this context the degradation of a MOS transistor can be measured as the number of occupied traps and the dynamics of this occupation must be better understood. In this paper we aim at a theoretical analysis for describing the density of occupied traps
in a semiconductor device and so to understand how a characteristic degradation process occurs in these devices and other similar devices.

So, first of all, we need to calculate the probability of a particular trap with constants $\tau_c$ and $\tau_e$ starting from state 0 (empty) and after an elapsed time $t$ being in this same state, which we denote as $p_{00}(t)$. This probability can be calculated by observing that $[1, 3]$

$$P_{01}(t + dt) = P_{01}(t)p(1 \rightarrow 1) + P_{00}(t)p(0 \rightarrow 1)$$

Figure 1. A simple schematic representation of a random telegraph signal caused by successive captures and emissions of charge carriers by a trap in the current of a CMOS transistor.

Figure 2. A scheme for a complementary metal–oxide–semiconductor device (a CMOS transistor), composed of a fine metal plate, an oxide (SiO$_2$), and a semiconductor (Si). A (gate–source) voltage $V_{GS}$ has the role of attracting the electrons to the top of the semiconductor near of the oxide. Another voltage $V_{DS}$ moves the charge carriers, generating a drain current. The charge carriers under a Fermi level can be captured or emitted to come back to the current over time, evolving according to the Fermi–Dirac statistics. These successive captures and emissions generate the known random telegraph signals.
where \( p(0 \to 1) = dt/\tau_c \) and \( p(1 \to 1) = 1 - p(1 \to 0) = 1 - dt/\tau_e \) and also \( P_{00}(t) = 1 - P_{01}(t) \). This leads to a simple differential equation: \( dP_{01}(t)/dt = \tau_c^{-1} - (\tau_e^{-1} + \tau_c^{-1})P_{01}(t) \). As we have \( P_{00}(0) = 1 \), its solution is \( P_{01}(t) = \tau_c(\tau_e + \tau_c)^{-1}[1 - \exp(-t/\tau_{eq})] \), where \( 1/\tau_{eq} = 1/\tau_e + 1/\tau_c \). Similar results can be obtained leading to \( P_{11}(t) = \tau_e/(\tau_e + \tau_c)[\tau_e + \tau_c\exp(-t/\tau_{eq})] \). Unless there are fluctuations in the current amplitude whose average \( \Delta \) depends on other microscopic factors of the device, this probability corresponds to the autocorrelation of the system \( A(t) = \langle \sigma(0)\sigma(t) \rangle \), where \( \sigma(t) \) corresponds to the state of the trap (occupied, \( \sigma = 0 \), or empty, \( \sigma = 1 \)). In the frequency domain this exponential decay of the autocorrelation for one trap is described using Lorentzians, since the power spectrum density, i.e., the Fourier transform of the autocorrelation, is

\[
S(f) = \int_{-\infty}^{\infty} e^{-2\pi ft} A(t) \, dt = \frac{4\Delta^2}{(\tau_e + \tau_c)(\tau_{eq}^2 + 2\pi f^2)}.
\]

The known \( 1/f \) noise results from the sum of these Lorentzians (a contribution of the many traps in the device). For more details about the origin of \( 1/f \) noise, see for example [4, 8, 14, 15].

So, coming back to relaxation phenomena, and starting from \( n(0) = 0 \) (all traps empty), we can calculate the average density of occupied traps at time \( t \):

\[
\langle n(t) \rangle = \left\langle \sum_{k=0}^{N_{tr}} \sigma_k(t) \right\rangle = \sum_{k=0}^{N_{tr}} k \Pr(k|n(0), t)
\]

where \( \Pr(k|n(0), t) \) is the probability that just \( k \) traps are occupied at time \( t \), with \( k = 0 \ldots N_{tr} \). But the traps have different constants \( \tau_e \) and \( \tau_c \) and, from that, we derive

\[
\Pr(k|n(0), t) = \sum_{C_k} \prod_{i=1}^{k} P_{01}(\tau_c^{(d_i)}, \tau_e^{(d_i)}; t) \prod_{i=k+1}^{N_{tr}} P_{00}(\tau_c^{(d_i)}, \tau_e^{(d_i)}; t)
\]

with \( C_k \) denoting every subset \( \{d_1, d_2, \ldots, d_k\} \) from \( \{1, 2, \ldots, n\} \). But \( \{\tau_c^{(d_i)}, \tau_e^{(d_i)}\}_{i=1}^{N_{tr}} \) are statistically independent and identically distributed, and we have

\[
\Pr(k|n(0), t) = \sum_{C_k} \frac{P_{01}(\tau_c, \tau_e; t)^{k} \cdot P_{00}(\tau_c, \tau_e; t)^{N_{tr}-k}}{\binom{n}{k}}
\]

where \( \tau = \int \int f(\tau_c)g(\tau_e) \, d\tau_c \, d\tau_e \), where \( f(\tau_c) \) and \( g(\tau_e) \) are probability densities for time constant times of capture and emission. Microscopically these quantities can be better understood. Actually, \( \tau_c \) and \( \tau_e \) have a thermal and a gate voltage dependence. Some more detailed approaches use quantum two-dimensional calculations of these quantities [10]. Here we use a known simplification proposed by Kirton and Uren [1], where \( \tau_c \) and \( \tau_e \) are random variables that follow the forms \( \tau_c = 10^p(1 + \exp(-q)) \) and \( \tau_e = 10^p(1 + \exp(q)) \), where \( p \in [p_{\min}, p_{\max}] \) and \( q = (E_c - E_F)/k_B T \in [E_v - E_F]/k_B T, (E_c - E_F)/k_B T \) are randomly distributed according to respectively a uniform and a U-shape distribution.
There is not much information about the density of states of the traps in the literature, but Wong and Cheng [7] show that for three different prepared gate oxides it follows a U-shape form.

Naturally, we must observe that \( \tau_{eq} = \tau_c \tau_e / (\tau_c + \tau_e) = 10^p \) corresponds to a uniform distribution of time constants (\( \tau_{eq} \)) on a log scale, as expected. Here, \( E_t \) and \( E_F \) are respectively the energy of observed traps and the Fermi level of the system, which is directly proportional to \( V_{GS} \) applied in the device. For our purposes, it is more interesting to switch to an average:

\[
\int \int (\cdot) f(\tau_c) g(\tau_e) \, d\tau_c \, d\tau_e \rightarrow \frac{\int_{p_{min}}^{p_{max}} \Omega(E_i) \, dp \, \Omega(E_i) \, dE_i}{\int_{E_v}^{E_c} \Omega(E_i) \, dE_i} \left( p_{max} - p_{min} \right)
\]

where \( \Omega(E_i) \) is the density of states of the traps in the interface.

Coming back to equation (1), after some straightforward calculations we have

\[
\langle n(t) \rangle = \sum_{k=0}^{N_{tr}} k \left( \begin{array}{c} n \\ k \end{array} \right) P_{01}(p, E_i; t)^k \cdot P_{00}(p, E_i; t)^{N_{tr} - k}
\]

\[
= N_{tr} P_{01}(p, E_i; t) = N_{tr} \int_{E_v}^{E_c} \frac{dE_i \, \Omega(E_i)}{1 + e^{-(E_i - E_F)/k_BT}} \, dE_i
\]

\[
= \frac{1}{(p_{max} - p_{min})} \int_{p_{min}}^{p_{max}} dp \left[ 1 - \exp(-10^{-p}t) \right].
\]

The second integral must be worked out better. Making a suitable change of variable \( p = -\log_{10}(u/t) \), \( dp = -\ln^{-1}10(du/u) \) and we have the temperature dependence separated from the time dependence via two integrals:

\[
\langle n(t) \rangle = N_{tr} \left( \int_{E_v}^{E_c} \frac{dE_i \, \Omega(E_i)}{1 + e^{-(E_i - E_F)/k_BT}} \right) \left[ \ln^{-1}10 \int_{10^{-p_{max}t}}^{10^{-p_{min}t}} \frac{du \left( e^{-u} - 1 \right)}{u} \right] \quad (2)
\]

which can be analyzed numerically. A particular case is when \( f(E_i) \) is uniform, and in this case we have

\[
\int_{E_v}^{E_c} \frac{dE_i \, \Omega(E_i)}{1 + e^{-(E_i - E_F)/k_BT}} = \frac{k_BT}{(E_c - E_F)} \ln \left[ \frac{e^{(E_c - E_F)/k_BT} + e^{(E_F - E_v)/k_BT}}{1 + e^{(E_F - E_v)/k_BT}} \right].
\]

If \( E_F = (E_v + E_c)/2 \), i.e., it is exactly in the middle of the band gap, this integral is numerically equal to 1/2 and there is no temperature dependence, i.e.,

\[
\langle n(t) \rangle_{\text{uniform}} = \frac{N_{tr} \ln^{-1}10}{2(p_{max} - p_{min})} \int_{10^{-p_{max}t}}^{10^{-p_{min}t}} \frac{du \left( e^{-u} - 1 \right)}{u}.
\]

A particularly simple case arises if we observe that the evolution of the occupation probability of a single trap, with time constants \( \tau_e \) and \( \tau_c \), is numerically equal to \( \lim_{N_{tr} \to \infty} \langle n(t) \rangle_{\text{uniform}}/N_{tr} \) when all traps have the same \( \tau_e \) and \( \tau_c \), which is given by

\[
\Pr(\sigma_i(t) = 1) = \frac{1 - \exp[-(1 + \beta)t/(\beta\tau_e)]}{1 + \beta}
\]
where $\beta = \tau_c/\tau_e$ is an important ratio considered in this context. Naturally $\Pr(\sigma_i(t) = 1) \to 1/(1 + \beta) = \tau_o/(\tau_e + \tau_e)$ when $t \to \infty$.

But what is the behavior of $\langle n(t) \rangle$ in a realistic case (i.e., when $\tau_c$ and $\tau_e$ are randomly distributed)? In this case we solve the exponential integral from (2) numerically. We adopt the usual values found in the literature for this problem ($p_{\text{min}} = 0$ and $p_{\text{max}} = 7$) which means a frequency ranging from 1 to $10^7$ Hz.

The continuous curve in figure 3 shows the time evolution of $\langle n(t) \rangle$ obtained theoretically (i.e. by numerical integration of equation (2)). The points corresponds to our MC simulations. For these MC simulations, we start from a given number of empty traps. For each time, each empty trap $i = 1, \ldots, N_{\text{tr}}$ becomes occupied with probability $p_i(0 \to 1) = 10^{-p_i(1 + e^{-q_i})^{-1}}$ and similarly an occupied trap becomes empty again with probability $p_i(1 \to 0) = 10^{-p_i(1 + e^{q_i})^{-1}}$, where $p_i$ is uniformly drawn in $[p_{\text{min}}, p_{\text{max}}]$, and here the same values ($p_{\text{min}} = 0$ and $p_{\text{max}} = 7$) were used. Similarly $E^{(i)}_t$ is uniformly drawn in $[E_v, E_c]$. For real devices, $E_F$ should change from $0.2$ to $1.0$ eV. First of all, $E_F$ corresponds to the middle of the band gap ($E_F \sim 0.6$ eV), $k_B = 8.617385 \times 10^{-5}$ eV K$^{-1}$ and $T = 300$ K, which leads to $q_i \in [-15.473, 15.473]$. We can observe an excellent agreement between the MC simulations and our theoretical equations, showing that in the semi-log plot in figure 3 the relaxation dynamics follows a logarithmic law:

$$\langle n(t) \rangle_{\text{uniform}} \sim A + B \log t$$

where we find $A = 31.80(15)$ and $B = 144.20(3)$. The uncertainties were obtained using error bars obtained from 16 independent runs of the program. We tested other temperature values but we did not find any difference, as expected when $E_F$ is in the middle of band gap in this case where a uniform density of states is considered.

Extending our results, we can compute the second moment:

$$\langle n(t)^2 \rangle = \sum_{k=0}^{N_{\text{tr}}} k^2 \Pr(k|n(0), t)$$

Figure 3. Time evolution of $\langle n(t) \rangle$ obtained directly by numerical integration of equation (3). The points corresponds to MC simulations performed under the same conditions.
which yields
\[ \langle n(t)^2 \rangle = N_{tr}\text{Pr}(k|n(0), t) + N_{tr}(N_{tr} - 1)\text{Pr}(k|n(0), t)^2 \approx \langle n(t) \rangle + \langle n(t) \rangle^2. \]

So we have
\[ \langle n(t)^2 \rangle \approx \frac{N_{tr}\ln 10}{2(p_{\text{max}} - p_{\text{min}})} \int_{10^{-p_{\text{max}}t}}^{10^{-p_{\text{min}}t}} \frac{d\ln u}{u} (e^{-u} - 1) \]
\[ + \frac{\ln^2 10 N_{tr}^2}{4(p_{\text{max}} - p_{\text{min}})^2} \left[ \int_{10^{-p_{\text{max}}t}}^{10^{-p_{\text{min}}t}} \frac{d\ln u}{u} (e^{-u} - 1) \right]^2, \]

which leads to
\[ \langle n(t)^2 \rangle \sim \phi(T, E_F)(A + B \log t + B^2 \log^2 t) \]
with \( A \) and \( B \) exactly as reported before.

Looking at the temperature dependence, we must analyze more realistic densities of states. After a detailed scanning of the plots for the densities of states, for the three prepared gate oxides (TCE oxide, reoxidized nitrided oxide, and nitrided oxide) found in [7], a fit with an eighth-degree polynomial, here described by \( \hat{\Omega}(E_t) = \sum_{k=0}^{8} \beta_k E_t^k \), was performed (see [2] for a more detailed discussion of this part). This excellent fit can be seen in figure 4.

Using these U-shaped densities of states or even their polynomial fit, we can calculate the temperature dependence:
\[ \varphi(T, E_F) = \frac{1}{Z} \sum_{k=0}^{8} \beta_k \int_{E_v}^{E_c} \frac{E_t^k dE_t}{1 + e^{-(E_t - E_F)/k_B T}} \]
(5)

with \( Z = \sum_{k=0}^{8} \beta_k (k + 1)(E_c^{k+1} - E_v^{k+1}) \) where then \( \langle n(t) \rangle \sim \varphi(T, E_F)(A + B \log t) \), showing that the temperature and Fermi level dependence are independent of time, i.e., the relaxation depends logarithmically on time for each fixed pair \((T, E_F)\).
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Figure 5. Density of occupied traps for different temperatures (323, 373, 423, 448, 473 K) using a real U-shape; we observe effects on the logarithmic law exactly as observed via experimental results obtained in [5]. The inset shows the amplification $\varphi(T)/\varphi(323)$ as a function of temperature for the three different oxides, showing agreement among them, indicating a universal linear behavior, $\varphi(T)/\varphi(323) \sim 0.18 T$.

Using Simpson numerical integration, we calculate $\varphi(T)$ and now the time evolution of $\langle n(t) \rangle$ is calculated according to equation (2). Taking motivation from experimental results, initially we study $\langle n(t) \rangle$ for a Fermi level set at $E_F = E_c = 1$ eV using the U-shape obtained from reoxidized nitrided oxide. Figure 5 shows $\langle n(t) \rangle$ for different temperatures. The inset in this same figure shows the amplification factor of the temperature: $A(t) = \varphi(T)/\varphi(323)$, since $T_0 = 323$ K (50°C) is the minimum temperature used in our calculations for the three different oxides extracted from [7]. We show a universal linear behavior, described by the relation $A(T) \sim 0.18 T$.

It is also interesting to study the dependence on the Fermi level. The Fermi level may be varied by changing the gate bias of the device as experimentally explored in [5]. We studied the dependence of $\varphi(T)$ as a function of $T$ for different values of $E_F$. Our results show that the curves showing the evolution of the relaxation as a function of time can be collapsed into a single one if multiplied by a suitable constant. This constant is $\varphi(T, E_F)$ (see figure 6). Hence, our results are in agreement with the experimental findings for the Fermi level dependence of the relaxation.

We also studied the dependence on the initial density of occupied traps. In this case, if the density of the initially occupied traps is lower than the equilibrium value, in the relaxation process the number of occupied traps increases logarithmically. On the other hand, if the density of initially occupied traps is higher than the equilibrium value, the density of occupied states decreases logarithmically in the relaxation process. MC simulation confirmed this behavior. MC simulations were performed starting from different initial densities of occupied traps $\rho_0 = 0, 0.1, 0.2, 0.3, \ldots, 1.0$, where the equilibrium value is $\rho = 0.5$. We can observe this behavior in figure 7.

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Figure 6. Fermi level dependence of $\varphi(T)$. 

Figure 7. The density of states increases logarithmically for $\rho_0 < 0.5$, and decreases for $\rho_0 > 0.5$. For $\rho_0 = 0.5$ we can see a constant behavior of the degradation, i.e., the number of occupied traps remains unchanged over time. The inset is a semi-log plot, showing the logarithmic behavior.

There is an important question that deserves a detailed discussion: what is the minimum constraint needed to lead to a log behavior of the density of occupied traps? Aiming to answer this question, we study the impact of trap distribution on the observed behavior. For electron capture at the interface, the defect state is well away from equilibrium, so the excess energy will be dissipated by a multiphonon emission. On the other hand a simple way to write $\tau_c$ is as

$$\tau_c \propto \frac{1}{\rho \langle v \rangle \sigma},$$

where $\rho$ is the density of particles in the drain current, $\langle v \rangle$ is the average thermal velocity of the carriers, and $\sigma$ is the average capture cross section. Writing explicitly $\tau_c \propto (1/\sigma)(1 + e^{(E_t - E_F)/k_B T})$, according to our previous definition, we have $\tau_c \propto (1/\sigma)(1 + e^{(E_F - E_t)/k_B T})$. 

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Figure 8. Upper plot: the density of occupied traps for two cases: (i) uniform distribution; (ii) triangular distribution. One can see a deviation of the logarithmic behavior at the borders (small and large values of time $t$). However, in the central part of the time axis (the $x$-axis), the curve can be approximated by a straight line. Lower plot: the time evolution curve for the density of occupied traps changing, $\Delta p^{(i)} = p_{\text{max}}^{(i)} - p_{\text{min}}^{(i)}$. Here $p_{\text{max}}^{(i)} = p_{\text{max}}^{(i-1)} - 1$ and $p_{\text{min}}^{(i)} = p_{\text{min}}^{(i-1)} + 1$, $i = 1, \ldots, 10$, and $(p_{\text{min}}^{(0)}, p_{\text{max}}^{(0)}) = (-10, 20)$. The arrow indicates increasing order of $\Delta p$. We can see an asymptotic convergence for the log behaviors as $\Delta p$ grows.

Therefore, we find $\tau = \tau_c \sigma / (\tau_c + \sigma_c) \propto \sigma^{-1}$. Kirton and Uren [1] suggest, for certain ranges and distributions of $\sigma$, that $p = \log \tau$ can be distributed according to a triangular distribution and not a uniform distribution. This should bring about deviations and distortions from logarithmic behavior for the density of occupied traps.

We also performed numerical experiments to check the possibilities. We consider a triangular distribution for $p$, according to

$$f(p) = \begin{cases} 
\frac{4(p - p_{\text{min}})}{(p_{\text{min}} - p_{\text{max}})^2} & p_{\text{min}} < p < \frac{(p_{\text{min}} + p_{\text{max}})}{2} \\
\frac{4(p_{\text{max}} - p)}{(p_{\text{min}} - p_{\text{max}})^2} & \frac{(p_{\text{min}} + p_{\text{max}})}{2} < p < p_{\text{max}}
\end{cases}$$
and we calculate \( I = \int_{p_{\text{min}}}^{p_{\text{max}}} dp f(p)[1 - \exp(-10^{-p}t)] \), which, unless the constants depend on the temperature and the Fermi level, is essentially the density of occupied traps.

It can be seen that there are deviations at the borders (the upper plot in figure 8). However, in the center of the time window (the x-axis), this can be approximated by a straight line (i.e., it can be assumed that it approximately follows a log behavior). In other words, it could be said that the log behavior may be observed as long as the fastest trap has a time constant much shorter than the lower border of the time window of interest, and the slowest trap has a time constant much larger than the longest time interval of interest. This is the case of practical interest, and also the case for most of the data found in the literature. See, for instance, [5,6]. Typically, the time interval used in experimental studies of the process of degradation in semiconductor devices is a window extending from microseconds to thousands of seconds. The time constants of the fastest and slowest traps usually span a much larger time interval, as observed from low frequency noise measurements [1].

However we performed an experiment looking at the time evolution of the density of occupied traps. We start from \((p_{\text{max}}^{(0)}, p_{\text{min}}^{(0)}) = (-10, 20)\), and we consider all pairs \((p_{\text{max}}^{(i)}, p_{\text{min}}^{(i)}) = (p_{\text{max}}^{(i-1)} + 1, p_{\text{min}}^{(i-1)} - 1)\), with \(i = 1, \ldots, 10\), such that \(\Delta p = p_{\text{max}} - p_{\text{min}}\) changes from 30 to 10. We can see that for large ranges, notorious for showing a logarithmic behavior (a straight line on a semi-log scale), the deviations occur as \(\Delta p\) becomes shorter, as in the lower plot in figure 8. The dashed line shows the logarithmic behavior, and the light green curve corresponding to \((-10, 20)\) shows exactly this inclination. The arrow indicates increasing order of \(\Delta p\).

In summary, our results corroborate the experimentally observed logarithmic relaxation of the density of the occupied traps via MC simulations and from theoretical analysis in complementary metal–oxide–semiconductor devices governed by Fermi–Dirac–Shockley–Read statistics [9]. Our results also corroborate the experimentally observed temperature dependence, which shows that the relaxation as a function of time at different temperatures may be collapsed onto a single curve using a suitable scaling factor. This behavior is experimentally observed, e.g. in [5]. The scaling factor is the function \(\varphi(T, E_F)\) of equation (5).

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