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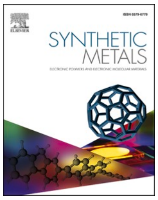

Non-exponential transients and the evaluation of stress in (disordered) organic thin film transistors

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ABSTRACT

In this work, the transient techniques for disordered organic thin film transistors are analyzed. A special emphasis is made on stress. Stress in this work is the continuous increase of the threshold voltage upon applying a gate bias. In this work a new stress evaluation method is presented that allows for a rapid determination of stress. Moreover, a figure-of-merit is proposed that can be applied to non-exponential transients, including those of stressing. The transients are compared to the empirical transient functions reported in literature that range from power-law to stretched exponential and logarithmic.

1. Introduction

Organic electronic materials differ from their inorganic siblings by often being of low crystalline quality, they can be called disordered materials. And it is this fact that makes them very difficult to study; classic measurement techniques often not applicable to organic materials. An example is transient techniques. These are often used to determine electronic levels in the conduction process. The time constant found in the relaxation curves yielding information about the energetic position of the involved levels. Especially when studied upon variations of the temperature. This work will study how generally transient techniques can be used for disordered materials and what their problems are. This with an emphasis on electrical stressing in thin film transistors (TFTs).

TFTs are important components in modern electronics and research alike. For research applications they are one of the simplest structures to measure material parameters such as charge-carrier mobility and thus serve as a testbed for developing new materials. The application in commercial devices is still limited by some detrimental side effects. These effects are mainly caused by a huge density of trap states. The most common and bothering problem is bias-stressing [1–3], which is a continuous drop of current when the bias is applied. Throughout this text this electrical bias-stress will simply be referred to as 'stress' or 'stressing'. Because the trap states responsible for the decreasing current are distributed in energy, any transients in such materials are non-exponential and this adds another complication to the analysis, as will be shown also here. Since stressing is also a transient effect, it also suffers from this phenomenon of non-exponential behavior and thus these two problems are related.

Stressing in thin-film transistors is the (mostly) unwanted effect that the threshold voltage V_T changes continuously upon application of the gate bias V_g. It is the result of trapping of free charge — electrons and holes — (or trap creation and instant trapping) in the channel onto localized states in the active layer or insulator [1,4]. The stressing is related to the amount of charge in the channel and not to the current [5]. Recently, Mathijssen, et al., have convincingly shown that for polytriarylamine (PTAA) on top of hexamethyldisilazane-treated silicon/silicon-oxide wafers the trapping is inside the insulator [6]. This is also supported by the fact that free-carriers induced by light, but without gate bias, do not cause any threshold-voltage shift [5]. Either way, the actual location of the trapping sites is not relevant for the current discussion on *how* to extract the parameters of stressing. Nor is the exact nature of the trapping centers relevant, be they water [7,8], or dangling-bond state creation (induced by hydrogen diffusion) [9–12], hydrogen-related trap-creation and impact ionization in the oxide [13], or anything else. These discussions are not the aim of this study.

In the current work two contributions to the research field of methods and techniques for studying disordered (organic) semiconductor devices are presented: 1) A new technique to measure stressing by a constant drain-source current method (called stress evaluation method, SEM), 2) A reliable parameter to describe the non-exponential transients (of any kind, not limited to stressing experiments). We start with presenting the relevant mathematical functions of non-exponential transients. And then present two new concepts into the electrical analysis techniques: a new way to measure stressing and a new way to parametrize general (non-exponential) transients.

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1.1. Evolution functions

Non-exponential functions described here are the result of a distribution of trap states. These functions are very difficult to work with, for reasons also shown here, and this complicates the analysis; finding useful information about the material and device is difficult.

When determined in a stressing experiment, the evolution of the threshold voltage follows an empirical relaxation function. Only very little theoretical work has been done — Powell et al. being one of the few exceptions [9]. Because of the empirical nature of the function, most modern reports in literature refrain from presenting the function and in many cases even present the data 'as is' without any form of linearization that might otherwise shed light on the function. Assuming (theoretically justifiable [4]) zero threshold voltage at $t = 0$, the general behavior can be described as

$$V_{\mathrm{T}}(t) = \Delta V_{\mathrm{T}}[1 - f(t)], \tag{1}$$

with t representing time, ΔV_{T} the total threshold voltage shift from $t = 0$ to $t = \infty$ and $f(t)$ a monotonically decreasing function, ideally dropping from 1 to 0 over time. ΔV_{T} is normally equal to the voltage drop across the insulator, meaning that eventually the threshold voltage approaches the gate bias $V_{\mathrm{T}}(\infty) = V_{\mathrm{g}}$, thus marginally closing the channel and reducing the current to zero. That is because in disordered semiconductors, stress-prone, devices the density of traps is so high that they can easily accommodate all induced charge and in a good approximation we can say that all charge winds up trapped sooner or later [4], and the channel is marginally closed. The functions $f(t)$ are in principle also useful for other kinds of transient behavior, like conventional current-transients $I(t)$, or capacitance transients, as in $I(t) = I_0 f(t)$, or $I(t) = I_0 g(f(t))$ in general, with g a function as discussed later on. The link between the stressing, current transients, and capacitance transients is that they are all related to trapping of charge on deep localized levels.

The simplest, most natural function would be a simple exponential, yet the most common function is the generalized stretched exponential, [5,11,14–17–20,21]

$$f(t) = \exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right], \tag{2}$$

with τ the time constant (that can depend via a power-law function on the bias [5]), and β (positive) an empirical factor that is related to the dispersion of time constants [5] and is equal to unity for simple exponential relaxation (a discrete trap). The time constant can also be thermally activated,

$$\tau(T) = \tau_{00}\exp\left(\frac{E_{\mathrm{a}}}{kT}\right), \tag{3}$$

with τ_{00} the pre-factor time constant, E_{a} the activation energy, T the absolute temperature and k Boltzmann's constant. The constant τ determines the time scale of the transient and can rapidly be found if we realize that, independent of the value of β, at $t = \tau$ the stretched exponential is $e^{-1} = 0.37$. In other words, when the threshold voltage has changed 63% of its total shift. Obviously, for this the total shift has to be known (the value of the function at $t = \infty$), which is not always easy, since the time of the experimenter is finite. We can, however, assume $V_{\mathrm{T}}(\infty) = V_{\mathrm{g}}$, which would be known.

A second class of functions is the power law,

$$f(t) = \left(\frac{t}{\tau}\right)^{-\alpha}, \tag{4}$$

with α a positive constant. See for instance the work of Ju, et al. [22], Ang et al. [23], Umeda, et al. [24], or Teo, et al. [25]. See also the work of Gomes, et al., of TFTs of sexithiophene [26] that finds a stretched hyperbola (another name for power-law) of the form

$$\begin{aligned} f(t) &= \frac{1}{\left[\exp\left(\frac{E_{\mathrm{th}}(t)-E_{\mathrm{A}}}{kT_0}\right)+1\right]^{1/(\gamma-1)}}, \\ &= \left(\frac{t}{1\ \mathrm{s}}\right)^{-\alpha}, \end{aligned} \tag{5}$$

with T_0 a temperature parameter, E_{A} an energy parameter, α and γ empirical power-law factors, and E_{th} an energy depending on time t, absolute temperature T and the attempt-to-escape frequency ν according to $E_{\mathrm{th}}(t) = kT\ln(\nu t)$. Like the (stretched) exponential, the power law has the property to marginally close the channel, $f(t = \infty) = 0$; $V_{\mathrm{T}}(t = \infty) = V_{\mathrm{g}}$. Ryu found that when stressing a device for a *fixed* amount of time, the voltage shift depends on the gate bias in this power law [5].

The time-scale parameter τ cannot be determined; τ^{α} has the same effect as the amplitude, i.e., it scales the amplitude and not the time, we might as well have defined the function as $f(t) = At^{-\alpha}$ (we define it as above for aesthetic reasons, to not be left with a unit of time raised to a power). In a log-log plot a power-law is linear and both a scaling in time by τ (horizontal-shift) and amplitude (vertical shift) have the same effect. For this reason, power laws are called (time)scale-free, or scalable functions [27]. These functions can also not be normalized in amplitude; for positive values α (as in our case), the function has a singularity at $t = 0$, and no amplitude can be defined, since it is infinite. Moreover, for any value of α integration (from $t = 0$ to ∞) results in infinity, either diverging at $t = 0$ or $t = \infty$. For this reason they are impossible to be used in statistical analysis, where probability functions (normalized to integral 1) are needed, for instance in forecasting [27].

Generally, the power-law function has the non-physical property that it has meaningless values for 'early' data with even a singularity at zero time; it gives negative threshold voltages below a certain time (in Eq. (4) in Eq. (1) for $t < \tau$). In other words, the function is only valid down to the first data point and cannot be extrapolated beyond it. However, the power-law function can be made integrable, scalable (in time and amplitude), and without singularities, by adding an offset time, τ, resulting in a so-called delayed power-law,

$$f(t) = (1 + t/\tau)^{-\alpha}, \tag{6}$$

which meets our requirements for a function $f(t)$. In a log-log plot this addition of τ is visible as a saturation to a constant value for small times,

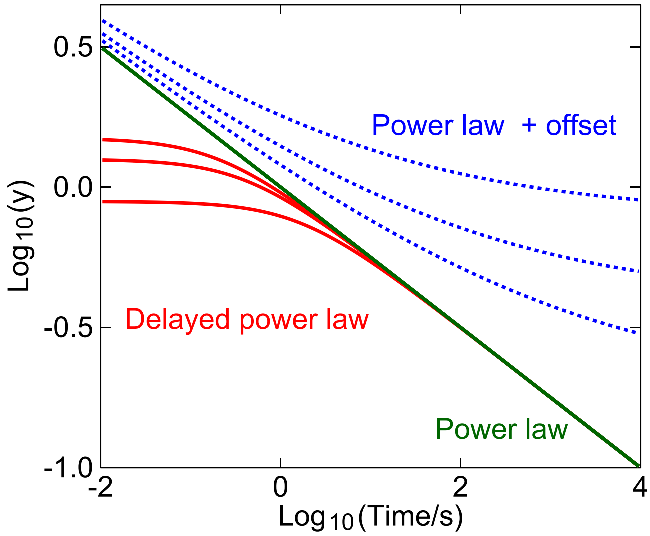

Fig. 1. Power law (central solid green line) and effect of adding offset in measured parameter y and time t. Function plotted is $y(t) = a/(t + t_0)^b + c$, with $a = 1$, $b = 0.25$ and offset $c = 0.2$, 0.4, 0.8 (dashed blue line) and $t_0 = 0.2$ s, 0.4 s, 1.6 s (solid red line).

where it would be a straight line without this addition, see Fig. 1. The measured power-law is then the result of the absence of data at short times compared to τ, which makes the delayed power-law above turn into a normal power law for $t \gg \tau$. Note that delayed power-laws behave 'nicely' in that they integrate to a finite value, where the power-law itself is non-integrable and integrates to infinity.

It has to be pointed out that the non-exponential functions described are caused by a distribution of trap states. However, they might also be cause by discrete traps if the kinetics are not first-order, but second-order instead (with the number of capture events proportional to the amount of free charge squared). In this case, it has to be noted, the power α in the delayed-power-law is unity. It is mentioned here for completeness sake.

The stretched exponential and the power-law can result from a convolution of individual simple mono-exponential transients, as shown by Newman [28]. Experimentally, the distribution of relaxation times has been proven by Schiener, et al., in a spectral hole-burning experiment [29]. Jurlewicz states that the results are from a relaxation-rate distribution of independently relaxing randomly-sized mesoscopic regions [30]. The difference between the stretched exponential and the power-law is that the latter results from ideal 'infinite' systems while the former is the result from physically finite, normally distributed systems [31]. Jonscher argues that hopping conduction and correlated many-body interactions to be the underlying reason of power-law behavior in the time domain [32]. Another relevant system, though not related to stressing, that results in power-law behavior is the capacitor filled with a conductive material (nonpolar liquid with surfactant) that yields $\alpha = 1$ or $\alpha = 0.75$ [33].

At first sight even stranger is the class of logarithmic functions,

$$f(t) = 1 - [\ln(t/\tau)]^{1-\gamma}, \tag{7}$$

for instance presented by Kaneko and coworkers. They find a logarithmic function of the form [10]

$$V_{\mathrm{T}}(t) = V_{\mathrm{g}}^{\delta} \times [\ln(t)]^{1-\gamma}\exp(-\Delta E/kT), \tag{8}$$

or the simple logarithmic function of Suresh and Muth [34]. (A gate-bias dependence in stressing functions can be caused by the field-dependence of the underlying process [9]). Note that also here for early times the function results in unphysical behavior, even imaginary stressing. And, even stranger, the way it is presented, this demarcation time is always 1 s (we intrinsically assume that t in the logarithm is divided by 1 s, to make it conform the SI units; the logarithm of time does not make sense). This just demonstrates the empirical nature of the function. Earlier, Schoonveld, et al. [3], used an off-set version of the logarithm, namely

$$\begin{aligned} V_{\mathrm{T}} &= \Delta V_{\mathrm{T}}\ln(t/\tau + 1) \\ &= \Delta V_{\mathrm{T}}\ln(t'/\tau), \end{aligned} \tag{9}$$

with $t' = t + \tau$, which has the advantage to give meaningful values for all t. This seems to give excellent results and is based on earlier work of Powell, et al., for silicon [9]. Powell et al., observe both logarithmic as well as power-law behavior and attribute the first to temperature-independent charge trapping (tunneling to traps in the insulator) and the latter to thermally-activated defect creation in amorphous silicon transistors [9]. It is as this moment not clear if these ideas can be transposed to organic TFTs.

Of these three classes of functions, two of them can easily be linearized. The power-law function is a straight line in a so-called log-log plot. Reasoning the other way around, if we see data plotted in a log-log plot that fall on a straight line, we know the data behave according to the power law. Examples are abundant in literature [9,35]. The third function presented here, the log function (Eq. (7)) is obviously linear if the time axis is in a logarithmic scale, and once again, when we see a straight line in a log-lin plot, we know that we have selected correctly the log function [9,34]. For the stretched exponential there is no easy procedure available to linearize the plot, which is unfortunate, since "scientists, to prove their models, like straight lines and peaks" (author's private phrase).

For all these cases, the steady state final value must be known, since the function is relative to the final value. This value has to be known with extreme quality, since a lot of information can still be retrieved for long times, when $f(t)$ approaches zero and determining small deviations from a non-zero offset is not easy. For this reason, measurement techniques that result in a final value of 0 are preferred, such as current transients (to be discussed later).

While mathematically they look dissimilar, in practice, under some conditions these functions are manifestations of the same general function. As an example, the logarithmic function is a special case of the power-law function for small α (or t). This can be understood if we series-expand the power-law function and approximate to first order ($|\alpha \ln(t/\tau)| \ll 1$)

$$\begin{aligned} A \times \left(\frac{t}{\tau}\right)^{-\alpha} &= A\sum_{n=0}^{\infty}\frac{\alpha^n[-\ln(t/\tau)]^n}{n!}, \\ &= A[1 - \alpha\ln(t/\tau)] + \mathscr{O}\left([\alpha\ln(t/\tau)]^2\right). \end{aligned} \tag{10}$$

The same can be done with the stretched exponential ($|\beta\ln(t/\tau)| \ll 1$)

$$\begin{aligned} B \times \exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right] &= \frac{B}{e}\left[1 - \beta\ln(t/\tau) + \frac{\beta^3\ln^3(t/\tau)}{6} + \frac{\beta^4\ln^4(t/\tau)}{24}\dots\right], \\ &= \frac{B}{e}[1 - \beta\ln(t/\tau)] + \mathscr{O}\left([\beta\ln(t/\tau)]^3\right). \end{aligned} \tag{11}$$

And for the log functions:

$$C \times \left\{1 - [\ln(t/\tau)]^{1-\gamma}\right\} = C[1 - \ln(t/\tau)] + \mathscr{O}(\gamma). \tag{12}$$

In other words — comparing Eqs. (10), (11) and (12) — for small exponents α, β and γ, and small times t (short measurements) these functions are indistinguishable from each other. Note that the (arbitrary) choice of τ causes only an offset in the curves and has thus the same function as the constant '1'. The logarithmic function has in fact only two parameters instead of the given three and τ loses any meaning. For instance, the three parameters A, α and τ can be translated into two parameters a and b:

$$\begin{aligned} &A[1 - \alpha\ln(t/\tau)] = a - b\ln(t), \text{ with} \\ &a = A[1 + \alpha\ln(\tau)], \\ &b = A\alpha. \end{aligned} \tag{13}$$

This implies that for small α and β the power law and stretched exponential, respectively, can be fit with *any* τ, and the time-scaling parameter τ is thus meaningless. We will see examples of this function.

Also, the stretched exponential can be directly converted into a (positive) power law, when we realize that $\exp(x)$ is approximately $1 + x$ for small values of x ($t \ll \tau$). Thus

$$\begin{aligned} &\exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right] = \sum_{n=0}^{\infty}\frac{1}{n!}\left(-\frac{t}{\tau}\right)^{n\beta} \\ &\approx 1 - \left(\frac{t}{\tau}\right)^{\beta}, \end{aligned} \tag{14}$$

which is a variation on the power law that can also sometimes be found in literature [5].

In any case, the logarithmic functions are obviously incorrect for all time scales, since it is unphysical that currents and threshold voltage shifts change sign. Thus, for long times the approximations can no longer be made. In practice, sometimes extreme long time scales of measurement are needed to arrive at this point and to be able to arbitrate between the various models. In most cases, any of the empirical functions is adequate, although for philosophical reasons we have a preference for the power-law, see our work on the conduction mechanism (Ref. [36]). As an example, the power law saturates and a good parameter is the time it takes to achieve half the total stress. However, to find this time, the total stress has to be determined and that may take a long time indeed.

In conclusion, the stretched exponential is a real-life case of the more theoretical power-law and the logarithmic function is an extreme case of the power law or the stretched exponential. In practice, though, even stranger functions can be found.

We will now give an idea on how transient functions can be based on the underlying activation of processes. In a very simple example, if free charge is trapping on discrete deep immobile states with a thermal activated time constant given by Eq. (3), then the resulting transient is mono-exponential. If we have a distribution in thermal-activation energies, or in general a distribution in time constants, then we can expect intricate transient shapes, depending on the distribution function of time constants and activation energies. We call this function here a ’density of states’ DoS (because it can easily be mapped to a real density of states with unit $\mathrm{m}^{-2}\mathrm{J}^{-1}$).

As an example, consider the situation of a normalized uniform boxcar DoS for the activation energies, relative to a discrete level like the bottom of the conduction band. See the DoS(E_a) shown in Fig. 2a,

$$\mathrm{DoS}(E_a) \propto \begin{cases} \dfrac{1}{E_1 - E_0} & E_0 < E_a < E_1 \\ 0 & \text{elsewhere} \end{cases} \qquad (15)$$

(unit: J^{-1}). With the relaxation time τ depending on the activation energy given by Eq. (3), we find a distribution of time constants given by

$$\begin{aligned} \mathrm{DoS}(\tau) &= \mathrm{DoS}(E_a)\frac{dE_a(\tau)}{d\tau} \\ &= \frac{kT}{E_1 - E_0}\cdot\frac{1}{\tau}, \end{aligned} \qquad (16)$$

a distribution shown in Fig. 2b. The total transient is then a sum of the contributions of the components of the DoS function,

$$\begin{aligned} y(t) &= \int_0^\infty \mathrm{DoS}(\tau)\exp(-t/\tau)d\tau \\ &= \frac{kT}{E_1 - E_0}[\mathrm{Ei}(-t/\tau_1) - \mathrm{Ei}(-t/\tau_0)], \end{aligned} \qquad (17)$$

with Ei the exponential integral function (`expint` in Octave). As can be seen by the linearity in log-lin plots (Fig. 2), this transient very much resembles the logarithmic form of Table 1. While the slope of this plot is not a meaningful parameter, because it depends on the total amplitude of the transient, it is proportional to the temperature T.

On the other hand, a normalized exponential distribution function DoS(E_a) of the form

Table 1

Transient functions $f(t)$. To linearize a plot, in any case, the offset in the measured parameter must be (well) known, at least the value at $t = \infty$, which might be found by fitting. One then plots y relative to this value y_0.

Function	Reference	Linearized plot	Slope(s)
Exponential	Eq. (2), $\beta = 1$	$\log(y)$ vs. t	$-1/\tau$
Stretched exponential	Eq. (2)	$\log(-\log(y))$ vs. $\log(t)$	β
Power law	Eq. (4)	$\log(y)$ vs. $\log(t)$	$-\alpha$
Delayed power law	Eq. (6)	$\log(y)$ vs. $\log(t)$	0, $-\alpha$
Logarithmic	Eq.(7)	y vs. $\log(t)$	*

y is the observed parameter (V_T, I_{ds}, etc) *: depending on the scale of y

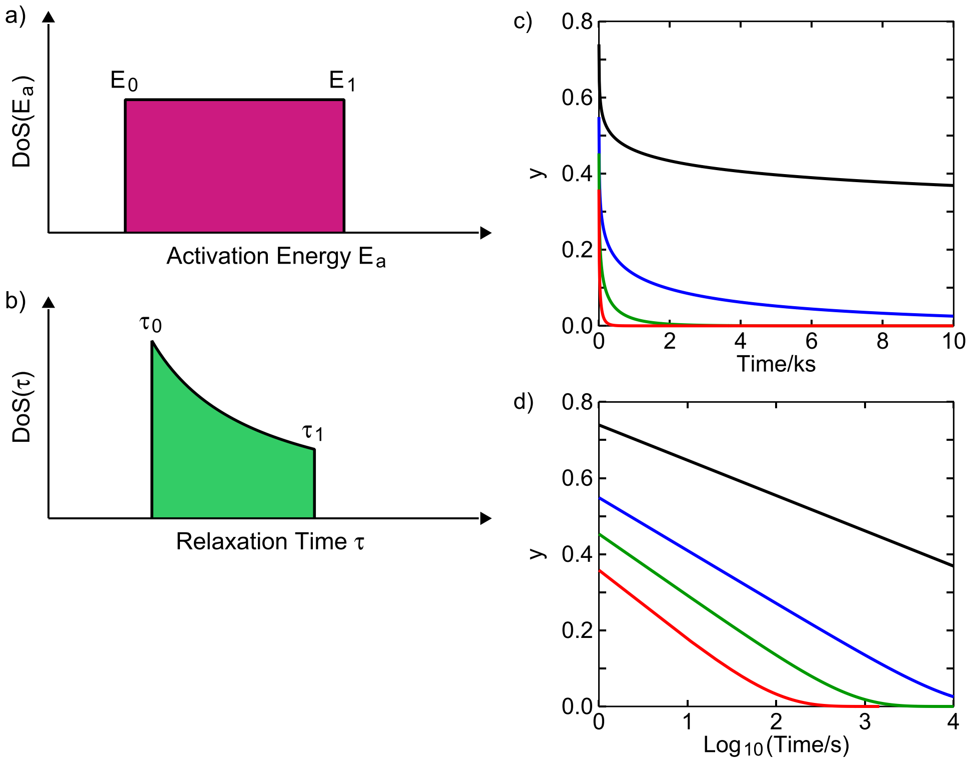

Fig. 2. A uniform activation energy distribution DoS(E_a) from E_0 to E_1 (a) translated into a distribution of relaxation times, DoS(τ)(b). This then results in a transient of the form given in Equation (17), shown in linear scale (c) and log-x scale (d). $E_0 = 26$ meV, $E_1 = 472$ meV, $\tau_{00} = 135$ μs. Temperatures T from highest to lowest curves: 200 K (black), 300 K (blue), 350 K (green), 400 K (red). The slope is proportional to T.

$$\mathrm{DoS}(E_\mathrm{a}) = \begin{cases} \dfrac{1}{E_{00}}\exp\left(-\dfrac{E_\mathrm{a}-E_0}{E_{00}}\right) & E_\mathrm{a} > E_0 \\ 0 & \text{elsewhere} \end{cases} \tag{18}$$

will result in a distribution function of relaxation times of the form

$$\mathrm{DoS}(\tau) = \frac{kT}{E_{00}}\exp\left(\frac{E_0}{E_{00}}\right)\left(\frac{\tau}{\tau_{00}}\right)^{-(kT/E_0+1)}\frac{1}{\tau_{00}}, \tag{19}$$

and a transient

$$y(t) = y_{00}\left(\frac{t}{\tau_{00}}\right)^{-kT/E_0} P\left(\frac{kT}{E_0},\frac{t}{\tau_0}\right), \tag{20}$$

with P the (upper) incomplete gamma function (`gammainc( , , "upper")` in Octave), and the prefactor y_{00} given by

$$y_{00} = \frac{kT}{E_{00}}\exp\left(\frac{E_0}{E_{00}}\right). \tag{21}$$

As can be seen by the linearity in log-log plots (Fig. 3), this transient very much resembles the power-law form of Table 1. The slope of this plot is proportional to the temperature T, namely $\alpha = kT/E_0$, and E_0 would be extractable through a temperature dependence $\mathrm{d}\alpha/\mathrm{d}T$.

One final remark at this place has to be made with respect to the temperature dependence. If the time window of the measurements in a transient is such that only *part* of the DoS effectively contributes, the rest either too fast or too slow to contribute, it might be so that changing the temperature merely shifts these states out of the measurement window, while others are shifted into it, thereby leaving the transient unaltered, or with suppressed differences. One might then come to the erroneous conclusion that the trapping to the states is not thermally activated. The experimenter has to be aware of this effect. Since temperature dependence is not studied in this work, we leave it here as a general comment.

1.2. *Parameter extraction of bias-stressing experiments*

The determination of the stressing parameters is normally done by applying a constant gate bias and every now and then determining the threshold voltage by rapidly measuring the transfer curve and fit a transfer function to it, yielding the instant values $V_\mathrm{T}(t)$. This method of determining the susceptibility of TFTs to stress has basically three huge drawbacks:

First, the parameters of threshold-voltage shifts are not simple exponentials but stretched exponentials or other functions instead, as described above. The span of time scales of these dynamics are huge; to accurately determine the parameters, the device has to be submitted to prolonged stressing experiments. This can be of the order of months rather than minutes. See for instance the work of Hekmatshoar, et al. [37] of amorphous silicon transistors. Second, an even larger problem consists of the fact that for measuring the threshold voltage the constant gate bias has to be interrupted. A transfer curve has to be measured that involves the scanning of this same gate bias. During this interruption of the stressing bias serious un-stressing effects can occur, especially considering the fact that the (un)stressing dynamics can also occur on all time scales. In the first millisecond already a huge threshold voltage shift (-back) can occur. This can also manifest itself in serious hysteresis in the transfer curves, thus even complicating the determination of the exact threshold voltage. While for inorganic materials this problem is not very big, since the un-stressing in these materials is significantly slower [38], for organic materials the stressing and un-stressing dynamics are comparable and a significant part of the stressing can disappear during the measurement of the threshold voltage. The total stressing magnitude can be underestimated [39]. The situation can also result in a distortion of the stressing dynamics function. For example, a theoretical power-law behavior can manifest itself as stretched exponential, or vice versa. The situation is aggravated when there is a need for comparison of stressing experiments across laboratories, or even between operators. The unstressing depends on the exact modus operandi. How fast a

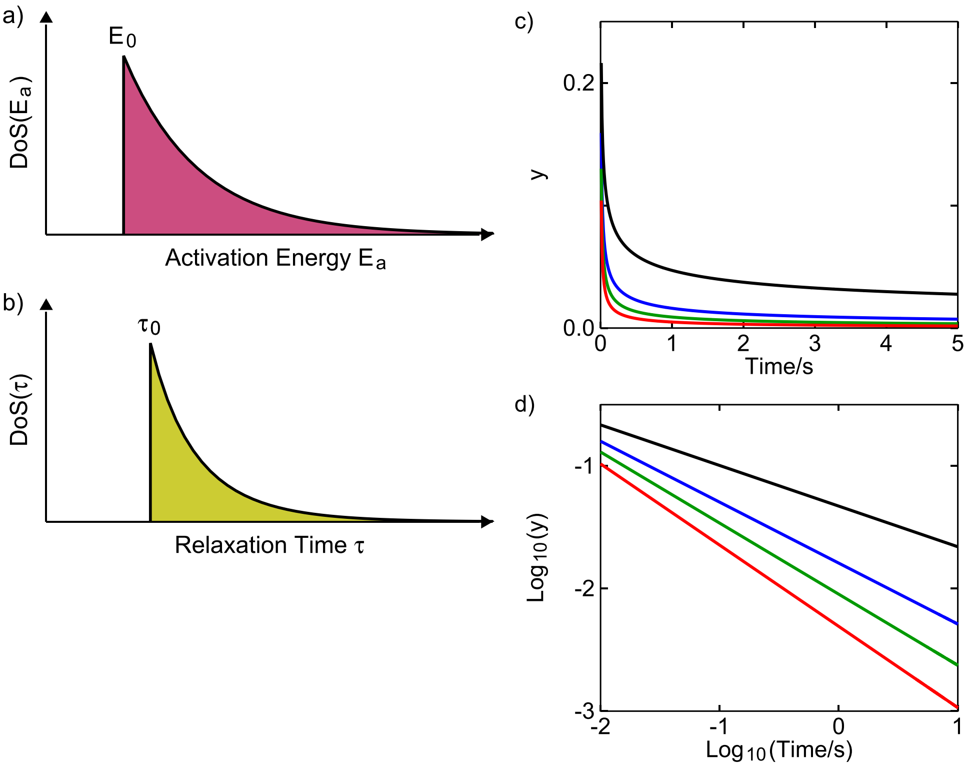

Fig. 3. An exponential activation energy distribution $\mathrm{DoS}(E_\mathrm{a})$ from E_0 to infinity (a) translated into a distribution of relaxation times, $\mathrm{DoS}(\tau)$(b). This then results in a transient of the form given in Equation (20), shown in linear scale (c) and log-log scale (d). $E_0 = 26$ meV, $E_1 = 472$ meV, $\tau_{00} = 135$ μs. Temperatures T from highest to lowest curves: 200 K (black), 300 K (blue), 350 K (green), 400 K (red). The slope is proportional to T.

transfer curve is measured. How fast the operator can press the correct buttons (or how fast the automatic system can generate and issue the correct sequence of commands). Third, to reduce the effects of the problem mentioned in the previous paragraph, the number of times the stressing voltage at the gate is interrupted is kept to a minimum. For a complete stressing experiment only sporadically the stress is interrupted and the threshold voltage measured, resulting in typically only some tens of datapoints. This low number complicates an accurate determination of the stressing parameters.

For these reasons, it is often difficult to ascertain the exact threshold-evolution function. In many cases either function will do and the use of one or the other is more the personal preference of the investigator. To overcome this, one could revert to plain-old steady-bias current transients, measuring the drain current $I_{ds}(t)$ under constant gate and drain bias, V_g and V_{ds}, respectively (also to be discussed in more detail later).

Before we continue we must now describe the currents in field-effect transistors (FETs). In standard FETs the current in the linear region is given by

$$I_{ds} = \frac{\mu C_{ox} W}{L}(V_g - V_T)V_{ds}, \tag{22}$$

with C_{ox} the insulator capacitance density (unit: F/m^2. $C_{ox} = \varepsilon_{ox}/d_{ox}$, with ε_{ox} the permittivity and the thickness of the insulator, respectively), μ the charge-carrier mobility, V_{ds} the drain-source bias, and W and L the channel width and length respectively. (See Fig. 4 for a description of the device parameters). The above equation can be transformed considering that the current is proportional to the free-charge mobility (μ), the free-charge density (ρ_F), and the electric field (V_{ds}/L),

$$I_{ds} = \mu \rho_F \frac{V_{ds}}{L}, \tag{23}$$

with

$$\rho_F = C_{ox} W (V_G - V_T). \tag{24}$$

(unit: C/m). In the linear region this charge density and the electric field are considered constant along the channel. Stressing is visualized as the disappearance of free charge, reducing ρ_F, observed as an increase of V_T. With the total induced charge equal to the free charge and trapped charge, $\rho = \rho_F + \rho_T$, equal to the voltage drop across the insulator multiplied by the insulator capacitance, we find that the threshold voltage is directly proportional to the amount of trapped charge,

$$\begin{aligned} &\rho_T = C_{ox} W V_T, \text{ or} \\ &V_T = \frac{\rho_T}{C_{ox} W}. \end{aligned} \tag{25}$$

In other words, current is proportional to free charge (Eq. (23)) while the threshold voltage is proportional to trapped charge (Eq. (25)) and the gate voltage is proportional to total charge.

To complicate things, for organic TFTs, a power law is predicted and found for this current, because the amount of free charge does not only depend on time (slow trapping), but also on gate bias (fast trapping), it can be adequately modeled by [4]

$$I_{ds} = \frac{\mu C_{ox} W}{L} \frac{(V_g - V_T)^\kappa}{(1\text{ V})^{\kappa-1}} V_{ds}. \tag{26}$$

(The division by 1 V added to make the units correct). If we substitute our threshold evolution function in this (and assume that the final current is zero, as discussed above; $\Delta V_T = V_g$), then

$$\begin{aligned} I_{ds}(t) &= \frac{\mu C_{ox} W}{L}(V_g - \Delta V_T[1 - f(t)])^\kappa V_{ds} \\ &= \frac{\mu C_{ox} W}{L} V_g [f(t)]^\kappa V_{ds}. \end{aligned} \tag{27}$$

As an example, the power law and stretched exponential become

$$\begin{aligned} &I_{ds}(t) = I_0 (t/\tau)^{-\alpha\kappa}, \\ &I_{ds}(t) = I_0 \exp[-\kappa(t/\tau)^\beta], \end{aligned} \tag{28}$$

respectively. In other words, even in these complicated situations the functions mimic the threshold voltage functions; power-laws and stretched exponentials keep their shape (with $\alpha' = \kappa\alpha$, $\tau' = \tau/\kappa^{1/\beta}$, resp.). These can then be further approximated by logarithmic functions in cases where it is permitted, as described above.

The problem is that, while this might be *related* to stressing, it is not necessarily the same thing. Currents, for instance, might also be reduced by a reduction in mobility, $\mu = \mu(t)$. What is searched for is the evolution of the threshold voltage over time and not the mobility over time. Even assuming a constant transfer curve that is only shifted 'horizontally' along V_g, it will not be easy to determine the function $V_T(t)$ on basis of the evolution $I_{ds}(t)$, especially in the case the transfer curve is not linear (as above), as is the case in most organic TFTs. A different method is thus warranted that i) works under 'steady' (uninterrupted) conditions and ii) yields the threshold voltage shift as a function of time. This is what we present in the rest of this paper. We propose a measurement method that we label The Stress Evaluation Method (SEM for short). This method might speed up the evaluation of stress (first issue of the conventional stressing method discussed above), but more important is the quality of the measurements (second and third issue); stressing is not interrupted and we obtain a large number of datapoints. In the final part, we try to present a figure-of-merit (FoM) for non-exponential transients in general, and use the stressing experiments as an example, trying to find a reliable parameter that indicates the vulnerability of a device to stress. These two combined result in better quality in evaluation of stress.

Yet, if all observed non-idealities in organic TFTs can be ascribed to the *same* effect of trapping (and trap creation), and the manifestations in the mobility, hysteresis and stressing are just a matter of different time scales — as proposed by us [4] — then the same information should be contained in the stressing experiment $V_T(t)$ as in the current transients $I_{ds}(t)$. Indeed, these transients are also often non-exponential and we can use similar analysis methods for them. For this reason, in this work also current transients will be analyzed. In the next sections, we will first describe the experimental procedure, then present an alternative way to measure stressing (by constant current), and the present a way to generally analyze non-exponential transients exemplified by such stressing transients as well as conventional current transients.

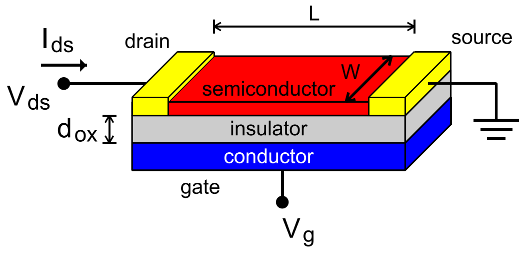

Fig. 4. A thin-film transistor and the definition of its dimensions and electrical parameters.

2. Experimental

The devices were from the FlexNet program. TFTs of (poly(triarylamine)), PTAA, on top of SiO$_2$ passivated by hexamethyldisilazane (HMDS); see the website for specification of the fabrication of the transistors [40,41] and one of the works of Bonea et al. [42]. The geometry is shown in Fig. 4, with the channel length L equal to 5 μm, 10 μm, 20 μm or 50 μm (50 μm used here), the channel width W equal to either 1000 μm or 10,000 μm. It has to be noted that the contact tracks of these are large and the effective device dimensions might thus be underestimated. The conductor was n-type As-doped silicon (2 mΩcm), and the insulator layer made of silicon oxide (relative permittivity equal to 3.9) with thickness d_{ox} equal to 220 nm. Electrodes of 30 nm Au on top of a 5 nm TiW adhesion layer deposited by sputtering and wet etching. The measurements were taken at room temperature in the dark at approximately 10^{-3} mbar pressure. For the current measurement a Keithley 487 was used, while for the gate voltage an Agilent HP66312A source was used. They were controlled by home-written software in Turbo Pascal running in MS-DOS on an Intel Pentium (I) computer. For the fast-measurement (up to seconds range) the internal buffer of the Keithley was used.

In the following a procedure for quantitatively determining the stress effect will be presented. The idea is as follows. Of the three parameters, V_g, V_{ds} and I_{ds} we keep two constant and measure the third. However, instead of the conventional steady-bias current transient — measure I_{ds} while keeping the bias V_g and V_{ds} constant — we keep the current and the drain-source bias constant and monitor the gate bias needed to keep this current, similar to the on-the-fly method of Ryu [5]. Note that this is not the same as using a constant-current source. The latter would imply keeping I_{ds} and V_g constant while monitoring V_{ds}. Fig. 5 shows the experimental procedure. The figure shows schematically some typical transfer curves (I_{ds} vs. V_g) along time. The system keeps the current constant (vertical axis) while monitoring the bias needed (horizontal axis) to keep this current. As can be seen, for transfer curves that are constant in shape but are only shifted along the horizontal axis, this found voltage has a constant offset from the threshold voltage; $V_g(t) = V_T(t) + V_{offset}$. Since we are only interested in threshold voltage *shifts*, this is a small price to pay. Apart from that, the threshold voltage is theoretically zero for a pristine device [4] — something that can also be verified experimentally long before or after the actual measurements, if needed — so that the absolute threshold voltage can be reconstructed. The advantage of the proposed method lies in the following facts: i) Steady conditions ii) No user intervention required, iii) A constant stream of data instead of obtaining a few intermittent data points. iv) No unstressing effects, allowing for rapidly and accurately determining the stressing function and parameters, as will be shown. v) The activation energy of the relevant process can be measured accurately. See the comment of Powell, et al. [9]. The biggest difference lies in the fact that stressing is not done at steady gate bias, but with a varying (increasing) gate voltage instead. Yet, we can determine rapidly how prone a device is to stressing.

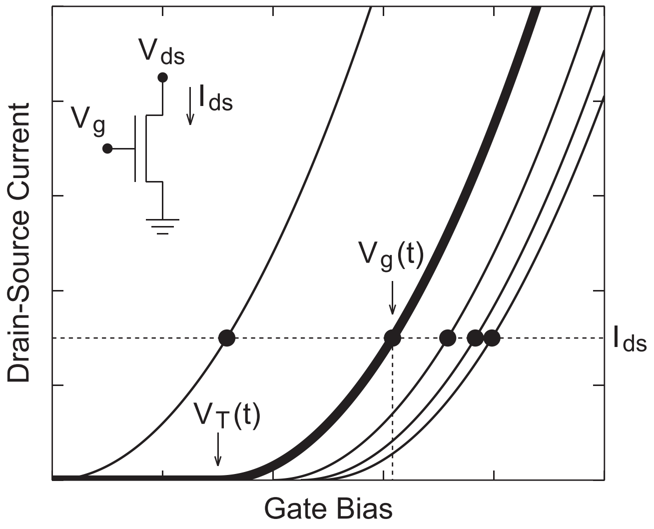

Fig. 5. Stress Evaluation Method (SEM). With a constant drain-source bias V_{ds}, the gate bias V_g that is needed to maintain a certain current I_{ds} is constantly monitored and adjusted. If the transfer curves are of constant shape and only shift horizontally, the measured gate voltage V_g is then equal to the varying threshold voltage V_T apart from a constant offset.

Note that we abandon here the classic procedure of stressing experiments. In these we kept a constant gate bias (V_g) and thus constant *total* charge (ρ) in the channel; free charge is slowly converted into trapped charge conforming our stressing function *f*(*t*), see the left panel of Fig. 6. In our scheme, we keep the amount of free charge constant, and monitor the bias V_g that is needed to sustain this. See right panel of Fig. 6. It will thus not necessarily result in a reproduction of the functions described above. Take for example the case in which trapping of free charge is simply proportional to the amount of free charge, $d\rho_T/dt = -d\rho_F/dt \propto \rho_F$, In a classic stressing experiment the threshold voltage will be exponential, $V_T(t) = V_g[1-\exp(t/\tau)]$, whereas it will be linear in the SEM experiment, $V_T = V_0 t/\tau$, according to Eq. (25). The important conclusion is that the stress functions *f*(*t*) mentioned above cannot directly be mapped to the proposed method. Yet, important information, possibly complementary, can be retrieved from the measurement curves. Moreover, since stretched exponentials and power-laws are caused by convolution of underlying parameters (for instance trap depth), we expect our transients to be similarly of these types.

3. Results and discussion

Figure 7 shows a result on a run-of-the-mill organic TFT, PTAA, measured with SEM. A problem with the SEM technique is that it takes some time to find the initial gate voltage needed to induce enough current in the channel. Remember that in our setup the finding of the gate voltage is not by hardware, but by software instead. Even with a smart search algorithm (of first derivative extrapolative guessing) it took in this case a little more than 20 s before the first data point was found. The reason is that the initial threshold voltage shifts are rapid and huge (a couple of volts per second) and the system cannot accompany these rapid shifts quickly enough because of the way it was done now: a software algorithm running on a 100-MHz computer. It is too slow to accompany the very large threshold voltage shifts observed with this new SEM method, shifts that are (possibly) not observed in other techniques. An electronic feedback control system would improve things substantially.

Apart from that, the curves are smooth, continuous and of high quality. Immediately the advantage of the method over standard stress-evaluation techniques is clear. A continuous stress evolution transient is found. Moreover, because of the steady uninterrupted conditions the transient is of high quality and has many data points. To the data a fit is made of the form

$$V_g(t) = \Delta V_g \times f(t) + V_{g0}, \tag{29}$$

with ΔV_g related to the amplitude of the transient and V_{g0} the final steady-state value or offset of $V_g(t)$, as described before. See Table 2 for the found values. Theoretically the stressing could go on forever, and the final voltage V_{g0} would be infinity, however, apparently it seems the gate voltage is going to settle at a final finite voltage V_{g0}, as evidenced by the fitting.

In this case, irrefutably, the function *f*(*t*) is a stretched exponential. A fit to the data was made, but the difference between the fit and the actual data is as good as invisible in the figure for the stretched exponential while clearly deviating for the power law. We can thus convincingly conclude that the stretched exponential is the adequate function for this particular stressing experiment.

However, we hit here upon another fundamental problem of non-exponential functions. While the fit is of superb quality (expressed in the parameter sum of normalized residuals squared divided by degrees of freedom [number of data points minus number of fitting parameters], $\chi^2/(\text{DoF} \times \sigma^2)$, which is lower for better fits and approaches unity in case the fitted function is correct and the noise σ is estimated correct, and also expressed by the R-squared parameter that ranges from 0 to 1 and is 1 for

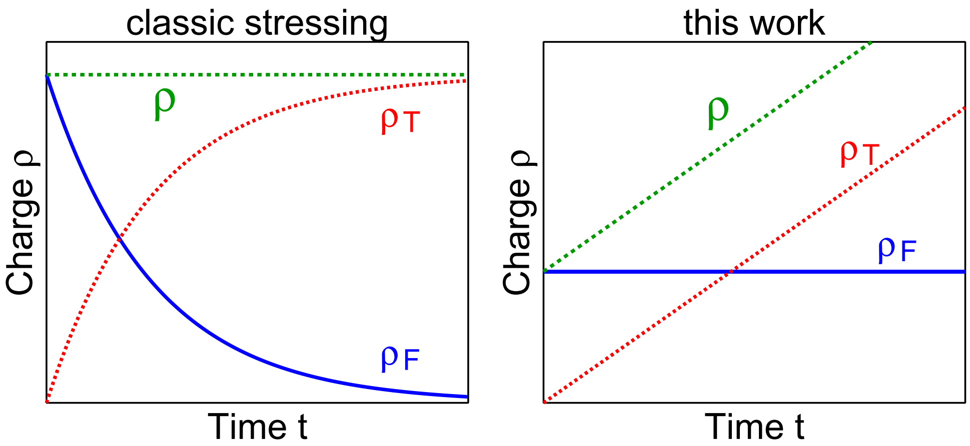

Fig. 6. Classic stressing: keeping a constant gate bias (and thus total charge ρ) where free charge ρ_F is slowly converted into trapped charge ρ_T according to the stressing function $f(t)$; $I_{ds}(t)$ is proportional to $\rho_F(t)$. The method presented here: Keep the amount of free charge ρ_F constant by constantly adjusting the gate voltage V_g, which is proportional to ρ_T. This gate voltage V_g is offset from the threshold voltage V_T; by monitoring V_g, we determine $V_T(t)$.

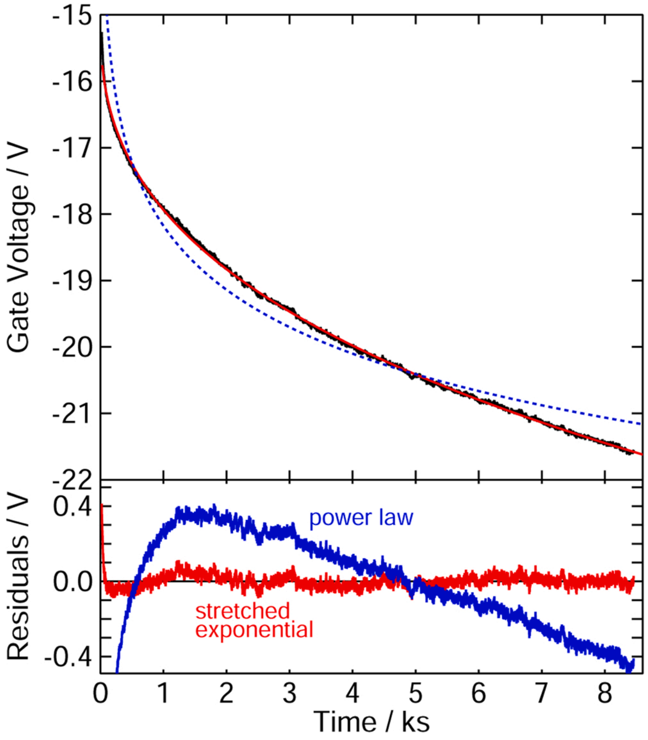

Fig. 7. SEM applied to a typical organic TFT, PTAA. Bias condition: $I_{ds} = -30$ nA, $V_{ds} = -1$ V. The data is fit to a stretched exponential (solid red curve; difference with data difficult to see) and a power law (dashed blue curve). The bottom panel shows the residuals after fitting. Note: because it is a p-channel transistor negative voltage has to be applied to the gate in order to open a conductive channel. The time is the one determined by the computer clock, and refers to the time after which the bias was switched.

Table 2

Comparison of fitting routines (to stretched exponential of Eq. (29)) applied to the SEM data of Fig. 7. χ^2 and R^2 are the parameters of the fitting presented by the various softwares and pertain to the fitting quality. χ^2 is the sum of squares of difference between observed value and expected value normalized by expected value, and here divided by the degrees of freedom (DoF; number of data points minus the number of fitting parameters) and the standard deviation ('noise') thus giving a goodness of fit; the smaller the better. R^2 is the coefficient of determination and indicates the quality of the fit (1 equals perfect fit to the model). As can be seen all fitting programs, while having different fitting value result is very good fits with similar fitting qualities.

Parameter	QtiPlot	Octave	Origin	SciDAVis	Variation
ΔV_g (V)	35.6 ± 1.9	39.3 ± 2.4	36.7 ± 2.09	35.76 ± 0.043	9.9%
τ (ks)	420 ± 69	560 ± 106	450 ± 79.6	419 ± 0.97	29%
β	0.411 ± 0.0027	0.407 ± 0.0038	0.410 ± 0.0028	0.4112 ± 0.0004	1.0%
V_{g0} (V)	−50.7 ± 1.9	−54.3 ± 2.4	−51.7 ± 0.78	−50.83 ± 0.046	6.9%
$\chi^2/(\text{DoF} \times \sigma^2)$	2.1	2.1	2.1	2.1	-
R^2	0.99938	-	0.99938	0.999997	-
FoM(100 s, 1000 s) (V)	1.717	1.726	1.731	1.725	0.8%
fom(100 s, 1000 s)	0.106	0.107	0.107	0.106	0.9%

a perfect fit), the stretched-exponential parameters found by fitting are far from well determined. This is evidenced by the fact that the *same* data, when fit by different fitting programs, although of visibly and numerically similar supreme fitting quality, result in significantly different function parameters (surprisingly, they are not even within each other's alleged error margins). Table 2 shows the fitting parameters found by four mathematical tools — QtiPlot, Octave, Origin and SciDAVis — that even claim to use the same Levenberg-Marquardt fitting algorithm. Apparently, minute differences can cause considerable changes of the results; the spread in found parameters is 9.9%, 29%, 1% and 6.9% for ΔV_g, τ, β and V_{g0}, respectively. This is caused by the interdependence of the fitting parameters and the intrinsic property of ill-determined functions, such as the stretched exponential, that the parameters are difficult to find. As an example, as a rule of thumb to adequately determine the parameters of a simple exponential, a time of the order of a couple of time constants should be measured. A stretched exponential is the result of a convolution of simple exponentials; time constants stretch to infinity and the condition for determining the parameters can thus never be met. In the above example, even the effective time constant τ falls far outside the measurement window (500 ks vs. 8 ks, resp.). In these cases the fitting is unstable. As we have reasoned, τ is no physically meaningful parameter and we are thus not surprised.

The divergence between the fitting results undermines the possibility of drawing conclusions from the parameters alone. The situation seems getting worse the more β deviates from unity and approaches zero. Fig. 8 shows the result of an experiment of repetitive SEM measurements of a similar transistor as used above (in fact, from the same multi-transistor die), with the second one starting about half an hour after the first one having finished. The behavior is very similar, apart from an offset. If we are looking for a parameter that captures and expresses the stressing

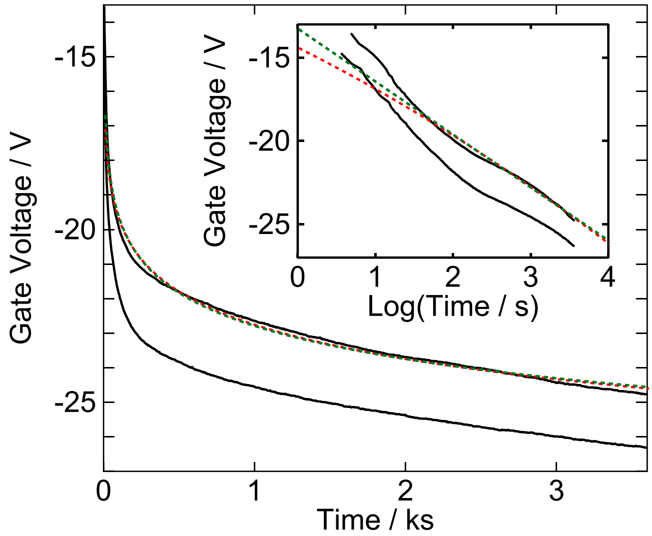

Fig. 8. Repeating an SEM experiment on the same device with $I_{ds} = -10$ nA, $V_{ds} = -1$ V; black curves (top: first, bottom: second). The stressing behavior is similar. To the first transient a stretched exponential, a power-law and a logarithmic function are fit (parameters in Table 3). All three give nearly the same result (the indistinguishable dashed curves in the linear plot). The inset shows the same plots in log-time scale. Due to the constant 1-Hz rate of sampling more data points are at the right side of the figure and the fitting seems to be of less quality for small times. This is just an optical effect.

behavior, it would be good if this parameter is stable and reproducible, also along devices of various geometries. To one of the transients a stretched exponential is fit (dashed curve), which is of much worse quality compared to the results in Fig. 7. The extraction of function parameters is not possible, due to the non-convergence of the fitting. The tendency is for the β to approach zero (even tiny negative in this case, $\beta = -0.032$) and simultaneously τ to approach infinity ($\tau = 1.1 \times 10^{14}$ s). To the same curve also a power law and a logarithmic function are fit, and these result in virtually the same curve; the stretched exponential and the power law are indistinguishable and convert to the logarithmic function for $\beta \to 0$ and $\alpha \to 0$, as predicted before (Eqs. (10) and (11)). The results/parameters are rather meaningless, even though the behavior is still more or less in line with the data. In such cases it is obvious that neither the fitting function, nor the fitting parameters shed any light on the stressing behavior of the device. The determination of an activation energy (Eq. (3)) then becomes even more dubious 3.

It is clear from the discussion above that the fitting function or the parameters themselves are not good figures of merit for the vulnerability of a device to stress. Like all non-exponential transients, these of stressing are hamstrung from the unreliability of extraction of the fitting parameters. For instance, the characteristic time τ easily varies many orders of magnitude for devices that seem to behave very similar. Classically, a method is to determine the time it takes to do half the total stressing. Obviously, to be able to do this, the value of the total stressing should be known. For that we need to measure to infinity or use fitting, in which case we are back to square one.

Table 3
Comparison of fitting functions applied to the SEM data of Fig. 8. R^2 and $\chi^2/\mathrm{DoF}\sigma^2$ are as described in Table 2.

	Fitting function *f(t)*		
Parameter	Stretched Exp.	Power Law	Logarithmic
ΔV_g (V)	−186	11000	1.380
τ (s)	1.1×10^{14}	1*	9.12
V_{g0} (V)	−2.84	−11000	−17.69
	$\beta = -0.032$	$\alpha = 0.00013$	
$\chi^2/(\mathrm{DoF} \times \sigma^2)$	38	38	38
R^2	0.988	0.988	0.988

*: Not a fitting parameter. Assumed unity

We propose here a DLTS-like (deep-level transient spectroscopy [4]) figure-of-merit (FoM) to parametrize non-exponential transients, with here an application to stressing experiments to determine the vulnerability of devices to stress. While this technique can be applied to any non-exponential transient data, we propose it here specifically for stressing data. The idea is, like in DLTS, to take two fixed points in the transient to come up with a reliable FoM:

$$\mathrm{FoM}(t_1, t_2) = V_g(t_1) - V_g(t_2). \quad (30)$$

In this, a FoM of 0 would mean that the device is either fully resistant to stress or is highly prone to stress (immediately fully stressed upon application of bias), and larger values mean severe stressing is taking place at that specific time window. Indeed, FoM is very similar to DLTS, in that it takes two values of the data and calculates the difference. What DLTS adds to it is that it is measured as a function of temperature and therefore results in a peak at a certain temperature. For low temperatures the transient is slow (nearly constant) and the DLTS signal is zero. At high temperature the transient is fast and has died out before the first datapoint and thus the DLTS signal is also zero. What FoM adds to this is the usage of the *entire* dataset to fit a function of choice – *any (reasonable) function will do* – and then on basis of these fitted parameters the two datapoints for FoM are *calculated*. One does not have to worry about weird parameter values found (such as demonstrated earlier) or unstable fitting; as long as the quality of the fit is good, the FoM parameter is reliable.

As an example, we show here a figure-of-merit with $t_1 = 100$ s and $t_2 = 1000$ s for the above device. We see in Table 2 that this parameter is independent of the fitting procedure and thus serves the purpose better than the separate fitting parameters ΔV, τ and β. This FoM parameter allows to be able to compare similar devices. To be able to compare between devices of different geometry, namely different insulator thickness, this FoM ideally is scaled. Ideally then it is scaled by the oxide capacitance. Alternatively, we can scale it by the first value, the scaled unitless figure-of-merit then being

$$\mathrm{fom}(t_1, t_2) = \left|\frac{V_g(t_1) - V_g(t_2)}{V_g(t_1)}\right|. \quad (31)$$

(Written in lowercase to distinguish it from FoM). In comparing device fabrication parameters, researchers agree on the times t_1 and t_2 to use in the FoM, or the scaled version (fom) if the devices have different geometry, and compare the values.

Like in DLTS, when determining a FoM value of a specific window (for instance the 100 s and 1000 s here), the FoM value gives information at this time scale window only. If other stressing time windows are needed to be studied, other time values have to be chosen and the measurement can take as long as before. However, the determination of the parameter at this window is reliable.

Next we analyze current transients (constant V_g and V_{ds}, measuring $I_{ds}(t)$). It is logical to assume that the current transients and the stressing have the same underlying physical phenomena. Fig. 9 shows a typical current transient of an organic transistor after switching-on the device (both V_{ds} and V_g from 0 to −30 volt). Once measured fast and then repeated slowly. The inset shows the same transients in a log-log plot ('power-law' representation). From the linearity of the latter format it is obvious that the transient follows the power-law ($\alpha = 0.25$, see the red dashed straight line) after some tens of seconds. Before that time the behavior is more stretched exponential ($\beta = 0.312$, $\tau = 87.5$ s; curved dashed line) or delayed power-law (shown is $\alpha = 0.25$, $\tau = 10$ s, see the green dashed curve). (The SciDAVis fitting parameters are presented in Table 4). This figure is very informative for the discussion on transients for the following reasons: It shows that the power-law is not physical for short times. According the power-law, the current would be infinite at $t = 0$. We can define a minimum time $t_{\min}$ that is custom for power laws

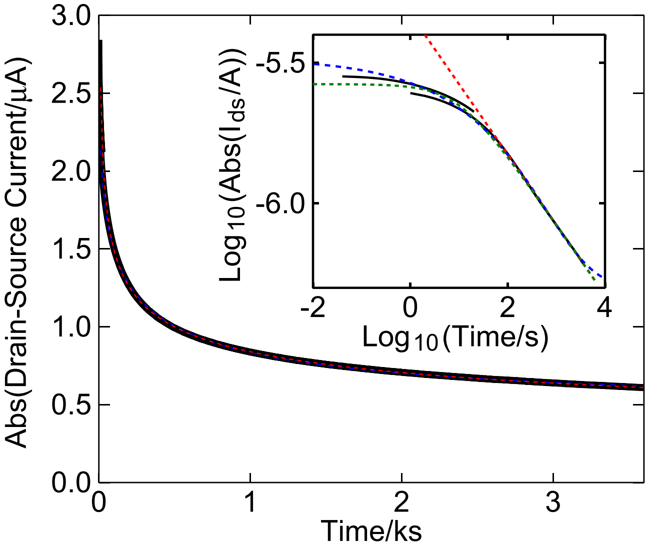

Fig. 9. Current transient of a run-of-the-mill organic transistor after a switch of $V_{ds} = V_g = 0 \rightarrow -30$ V (measured twice; once fast and once slow). The inset shows the same transients in log-log scale. After some tens of seconds the transient is clearly following a power-law, and can be fit well with a delayed power law ($\alpha = 0.331$), as shown by the linearity fit with a green dashed curve. The transient is also fit with a stretched exponential ($\beta = 0.312$, $\tau = 87.5$ s) for comparison. On the linear scale the fits are nearly indistinguishable and follow the data closely; fitting was done on the linear scale.

Table 4
Comparison of SciDAVis fitting functions applied to the current-transient data of Figure 9.

	Fitting function $f(t)$	
Parameter	Stretched exp.	Delayed power-law
ΔI_{ds} (μA)	2.79 ± 0.015	6.48 ± 0.019
τ (s)	87.5 ± 1.2	24.62 ± 0.12
I_0 (μA)	0.505 ± 0.0016	0.1876 ± 0.0015
	$\beta = 0.312 \pm 0.0016$	$\alpha = 0.3310 \pm 0.0008$

[28]. It shows that one can be mistaken by the stretched exponential parameters. In this example the fit on the linear scale is very good. However, in the log scale, no saturation (deviation from power-law; the log-log plot remains linear) is observed and for this reason the found relaxation time τ of 87.5 s has no meaning. The same material and devices can show power-law, stretched exponential and logarithmic behavior. There is often no consistency in the data of organic devices.

To show how non-exponential transient behavior manifests itself everywhere, the following technique was done. We short the drain and source and connect a voltage to this relative to the gate. This way the current measured at the gate is equal to the current filling the channel with charge, filling the interface traps. The advantage is that if the insulator is good, the insulator leakage is minimal and we have a situation in which the current guaranteed vanishes eventually; we thus have one fitting parameter less to care about. Fig. 10 shows such a typical transient. The data represented in a log-log plot shows that they reasonably follow a power law with $\alpha = 0.2$. This value is deviating from the diffusion value of $\alpha = 0.5$ predicted by Chen et al. [43].

As mentioned before, the complex transients are caused by a convolution of mono-exponential functions. We can imagine a distribution of trap states in energy, with each energy then corresponding to the time constant according to Equation (3). The distribution of energies translates into a convolution of simple exponentials that results in complex functions such as power-laws and stretched exponentials. When this happens, the scaling parameter (time constant) loses meaning, and is often rather undetermined. As mentioned, to determine a time constant in a transient, a measurement time has to be at least several times this time constant. To reason the other way around, the time window of measurement then determines the time constants that are measured. When all time constants are present, like in the case of such complex functions are described here, always the outcome will invariable to observe these time constants in the transients. The range of time constants is given by, more or less, the earliest datapoint ($\tau_{min} = t_1$, or the resolution) to the extent time window, $\tau_{max} = t_n$. Moreover, or as a consequence, if we want to determine the activation energy of these energies through Eq. (3) we will not manage. Heating up the device will shorten all time constants according to Eq. (3), so it will merely shift a new range of traps into the measurement window. The transient will not change in shape (at best it will change in amplitude), and we'd conclude erroneously that the traps are not thermally activated. As such, determination of the thermal activation process can only be done with discrete single-time-constant exponentials, or containing very few time constants at most. An example is capacitance-transients in ZnO/GaN hetero-junctions [44]. In most cases here and for disordered materials such as most organic electronic materials, the time constant τ is rather a meaningless parameter.

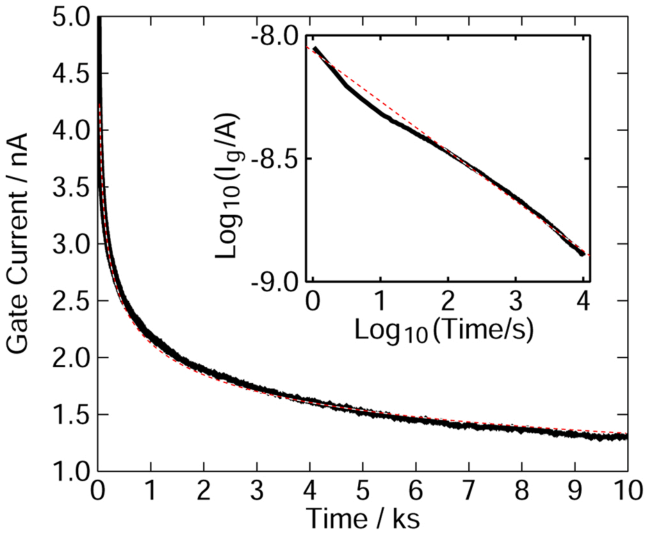

Fig. 10. Gate-current transient of a run-of-the-mill organic transistor after a switch of $V_d = V_s = 0 \rightarrow +20$ V, with V_g kept at 0. The inset shows the same transients in a log-log scale. The transient reasonably follows a power-law, especially in the log-log plot ($\alpha = 0.20$).

4. Summary

An analysis of transient data of disordered-materials electronic devices was described in this text. The difference between the relevant theoretical functions such as the power law and the stretched exponential is often too small to be noticeable. It is very difficult on basis of experimental data to arbitrate between the two. A good empirical fit is meaningless if not accompanied by a physical model justifying the type of fit and explaining the information contained within the fitted parameters values. Some of the problems of analysis were described, and in the current work two ideas were presented:

- A new technique with constant-drain-source-current for evaluating stress in disordered thin film transistors, SEM. The advantages of this technique are 1) An uninterrupted way, which avoids occurrence of unstressing' during the determination of the amount of stress (which happens because [un]stressing takes place at all time scales, even the ultrashort), 2) a continuous high-data rate which increases the quality of the information extracted. While the technique is not necessarily faster, it does yield higher quality results.

- A new parameter describing non-exponential transients, figure-of-merit (FoM). Since the classic parameters of the functions shown in the introduction cannot reliably be estimated, a new parameter is warranted. This is useful in, among other things, evaluating stress transients as mentioned above.

These may help researchers in the complex field of disordered semiconductor materials.

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CRediT authorship contribution statement

Peter Stallinga: Data curation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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