Transient photoresponse in amorphous In-Ga-Zn-O thin films under stretched exponential analysis

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We investigated transient photoresponse and Hall effect in amorphous In-Ga-Zn-O thin films and observed a stretched exponential response which allows characterization of the activation energy spectrum with only three fit parameters. Measurements of as-grown films and 350 K annealed films were conducted at room temperature by recording conductivity, carrier density, and mobility over day-long time scales, both under illumination and in the dark. Hall measurements verify approximately constant mobility, even as the photoinduced carrier density changes by orders of magnitude. The transient photoconductivity data fit well to a stretched exponential during both illumination and dark relaxation, but with slower response in the dark. The inverse Laplace transforms of these stretched exponentials yield the density of activation energies responsible for transient photoconductivity. An empirical equation is introduced, which determines the linewidth of the activation energy band from the stretched exponential parameter β. Dry annealing at 350 K is observed to slow the transient photoresponse. © 2013 American Institute of Physics.

INTRODUCTION

Amorphous In-Ga-Zn-O (a-IGZO) thin films have drawn great attention ever since 2004, when a thin film transistor (TFT) using a-IGZO as channel material was demonstrated.1 Compared with current TFTs, which are typically based on amorphous silicon (a-Si) or polycrystalline silicon (p-Si), a-IGZO-based devices are advantageous owing to their high mobility and ease of manufacturing. The typical mobility of a-IGZO thin films exceeds 10 cm2/Vs, larger than that of a-Si by an order of magnitude. This higher mobility is essential for making displays with superior resolution and faster refresh rates.2,3 p-Si, which has a larger mobility, suffers from inhomogeneity over large areas. In contrast, a-IGZO can be uniformly deposited over a large area at room temperature.2,4 This not only enables large area manufacturing at reduced cost but will also make the fabrication process compatible with the emerging flexible substrate techniques, which cannot withstand high processing temperatures.3,5 Due to its transparency, high mobility, and manufacturability, a-IGZO is already transitioning to industry use as a channel material for thin film transistors in flat panel displays.4,6–8

However, many reports have shown a large and slow transient photoresponse in a-IGZO under ultraviolet (UV) illumination.9–12 Until this photoresponse is properly characterized, data reported on semiconductor a-IGZO may be suspect since the sample properties can change even days after exposure to light. While this photoresponse raises concerns about reliability of devices based on a-IGZO, it highlights the need to minimize the photoconductivity effect for transistor applications, and also indicates new possibilities to utilize this transient photoconductivity to design new optoelectronic devices.13,14 Thus, more careful studies of the photoconductivity response in a-IGZO are warranted.

Transient photoconductivity can be used to deduce the density of energy levels within the mobility gap. In resistive crystalline semiconductors with point defects, this is generally referred to as photoinduced current transient spectroscopy (PICTS or PITS),27,28 and involves transients on time scales less than 1 sec. This method is a specific case of the more general term, deep level transient spectroscopy (DLTS), which considers both photoinduced and capacitive transients.29,30 In general, one can solve the inverse Laplace transform of the data numerically to deduce the density of trap states. Several methods – multi-exponential DLTS,31 direct fitting,32 and Tikhonov’s regularization33 – have been introduced for transient analysis.

For amorphous materials, on the other hand, the transient time scales can last as long as months, and the analysis goes under the name photoconductance transient spectroscopy.34–36 One difficulty of Laplace transforms of raw data is that they often introduce spurious noise and unphysical discontinuities in the result, and can be affected by the choice of extrapolation beyond the measured data range. A previous study of a-IGZO thin films used six fit-parameters—three decay times and their weighted amplitudes—to fit the photoconductivity decay.9 However, in amorphous materials, a continuous energy spectrum of thermally activated states is expected, which is known to fit well to a stretched exponential having only three fit parameters.15 Stretched exponential fits have been successfully employed to characterize the dark relaxation in a-Si (Refs. 15, 19, and 20) and many other material systems.21–23 Such fits have only three, uniquely determined

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fit parameters which correspond to a peaked continuous energy spectrum.

In this work, the transient photoconductivity of a-IGZO thin films was measured at various illumination conditions and temperatures, and the results are observed to fit well to a stretched exponential. The parameters in the stretched exponential fit are analyzed, and an empirical relation between the stretching exponent and the energetic bandwidth is presented. The stretched exponential fit is able to describe the dark decay response for all samples measured under different conditions, and the stretched exponential appears to describe the photoconductivity response during illumination as well, with a different set of stretch parameters than during relaxation. From the stretched exponential fit, we deduce the activation energy distribution and discuss the influence of deposition conditions such as oxygen pressure. The stretched-exponential parametrization developed here provides an empirical basis for quantifying and comparing transient photoconductivity in a-IGZO films.

**EXPERIMENT**

Three different a-IGZO films were grown by pulsed-laser deposition (PLD) at different O₂ partial pressures. A 248 nm KrF excimer-laser with a 25 ns duration, operated at 2 Hz, and a beam energy set to 200 mJ/pulse was used. The beam was focused to a 1 mm ×2 mm spot on the target material. A dense, hot-pressed, ceramic InGaO₃(ZnO)₂ target was used. To prevent localized heating, the target was rotated at 5 rpm and the laser beam was rastered. The target-substrate separation was fixed at 10 cm. The films, ~200 nm thick, were deposited at 25°C on borosilicate glass substrates. Film thickness was measured using a spectral reflectometer (Filmetrics F20). The samples were deposited in an oxygen pressure of 5, 10, and 15 mTorr, to change the initial carrier concentrations by orders of magnitude.

All electrical characterizations were conducted in a He-flow cryostat operating between 300 K and 350 K. The illumination was provided by a 405 nm wavelength UV LED light source placed around 10 mm above the sample and operated either with the maximum illumination current of 10 mA or in the dark state with no current. The cryostat provided a stable temperature to within 5 K. The Van der Pauw method was employed to measure the film conductivity σ. A superconducting magnet sweeping between −2T and 2 T was used for the Hall measurements, through which the carrier density n and mobility μ of the samples were determined. Because each magnet field sweep took 11 min, the n and therefore μ values had larger error at the start of illumination or at the start of a dark state, when σ was changing rapidly.

To investigate the transient photoresponse in a-IGZO, we recorded the change of conductivity, carrier density, and mobility over an extended time scale, at least 24 h for photo-excitation followed by 24 h for dark relaxation. This cycle was repeated 3 times for each sample: first at 300 K (as-grown state), then at 350 K (annealing state), and then again at 300 K (post-anneal state). The samples were mounted on a copper strip to ensure proper thermal monitoring and a uniform temperature during annealing. The copper strip has a heating resistor mounted to heat up the samples to 350 K, and a thermometer mounted to monitor temperature.

**RESULTS**

We illuminated the samples using red (630 nm), green (565 nm), blue (430 nm), and UV (405 nm) LEDs in an otherwise dark environment. Significant photoresponse was only observed under blue and UV illumination. The energy corresponding to blue and UV wavelengths is comparable to the band-gap of a-IGZO (~3 eV), indicating that the photoresponse comes mainly from electrons excited directly from the valence band to the conduction band. Therefore, we chose the UV LED with 405 nm wavelength and excitation energy 3.06 eV as light source for all further experiments.

For the as-grown samples deposited at oxygen pressure \( P_{O_2} = 5, 10, \) and 15 mTorr, we determined their carrier densities by Hall measurements. The black dots in Fig. 1 show the initial carrier density and the horizontal lines indicate the maximum and minimum carrier densities measured during photo-excitation and dark relaxation tests at 300 K and 350 K in dry He-gas ambient. There is a general trend of decreased carrier density with increasing \( P_{O_2} \), which agrees with earlier reports on a-IGZO films of a different stoichiometry. Continuous illumination and dark relaxation caused carrier density to change significantly over time. For transistor applications, the sample with \( P_{O_2} = 15 \) mTorr is of most interest because it is the most semiconducting, showing the largest swing in conductivity due to extrinsic conditions. This sample also shows the largest factor of conductivity enhancement from the dark state, exceeding two orders of magnitude.

In all three samples, the photoexcitation response and dark relaxation exhibited fast response at short times and extremely slow response at long times. The black curves in Fig. 2 show the photoconductivity transient while the ultraviolet LED was first on and then off. For all three samples, even after a whole day of illumination, the conductivity did not reach a saturation value with the curves still showing a significant slope at the end of the day. Note in Fig. 2(a)
to the finite time for the magnetic field sweep, measured mobilities tend to have large error shortly after the LED was switched on or off, when carrier density was changing rapidly. Even with this error, mobility was constant to within a standard deviation of 5% for each sample, whereas conductivities changed up to orders of magnitude. Therefore, the large changes in specimen conductivity can be attributed principally to changes in carrier density and the mobility can be assumed constant.

Heating up the thin films should not only increase the rate of any thermally activated processes but may also alter the state of the film. Photoconductivity curves under as-grown (300 K), annealing (350 K), and post-anneal (300 K) conditions were compared. Fig. 3 shows the results for the $P_{O_2} = 15$ mTorr sample, which is most interesting for transistor applications and shows the largest relative photoresponse. Elevated temperature is observed to enhance both the photo-excitation and dark relaxation rates for this sample. When the temperature was lowered back to 300 K after annealing, both rates were suppressed, implying that the 350 K anneal results in changes in the thin film for our experiment conditions. Similar trends were also observed for samples deposited at $P_{O_2} = 5$ and 10 mTorr. Thus, thermal annealing may help improve device stability in that decay constants tend to be slower. Mobility for each a-IGZO sample remained stable even when heated, varying by less than 15% standard deviation for the $P_{O_2} = 10$ and 15 mTorr samples, and less than 6% standard deviation for the $P_{O_2} = 5$ mTorr sample.

During the photoconductivity measurements, the data collection was interrupted occasionally for Hall effect measurements. By sweeping magnetic field between $-2$ T and 2 T, carrier density $n$ at that time was determined. The mobility $\mu$ was deduced and plotted as a gray square in Fig. 2. Due to how the slope barely changes between day 1 and day 2, indicating the extreme slowing of the response at long times. This is in contrast to the previous works on a-IGZO which only illuminated for 3 h—insufficient time to characterize the time dependence of the illumination behavior—or on related crystalline ZnO films which revealed what appears to be a stretched exponential behavior during illumination that is neither explicitly mentioned nor analyzed. In the dark, the sample conductivity did not reach a steady-state value after a whole day of relaxation. As can be seen in Fig. 2, the rate of photoconductivity change under dark relaxation appeared to be significantly slower than the corresponding excitation rate under UV illumination for each sample.

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DISCUSSION

In Fig. 2, sample conductivity changed rapidly immediately after the LED was turned on or off, indicating the presence of short time constants in the photoconductivity response. On the other hand, even after a whole day of photo-excitation or dark relaxation, sample conductivity was still changing significantly, but at progressively slower rates. This suggests that multiple time constants are involved in the photoresponse of a-IGZO thin films. Note furthermore that the relaxation curves obey longer time constants than the excitation curves, and the time constants are different among as-grown, anneal, and post-anneal states, implying that different energetic transitions are relevant in each regime.

Photoconductivity changing over time \( t \) with several time constant \( \tau_i \) can be described by the equation:

\[
\sigma_{ph}(t) = |\sigma(t) - \sigma_S| = \sum_i \sigma_i e^{-t/\tau_i},
\]

where the photoresponse conductivity \( \sigma_{ph} \) is the difference between time-dependent sample conductivity and the asymptotic conductivity \( \sigma_S \) at long times. Depending on experimental conditions, \( \sigma_S \) is either the saturation conductivity under illumination or the final, relaxed dark conductivity when measured in the dark. The weighting factor \( \sigma_i \) is the conductivity amplitude associated with each relaxation time \( \tau_i \), which in turn is related to a thermally activated process with activation energy \( E_i \) (Refs. 9 and 24)

\[
\tau_i = \frac{1}{\nu} e^{E_i/k_B T}.
\]

Here, \( \nu \) is the attempt-to-escape frequency, assumed to be the same for all activation energies, \( k_B \) is Boltzmann’s constant, and \( T \) is the sample temperature.

There are several possible microscopic mechanisms that may lead to the observed activation energies. According to the previous studies, carrier trap model failed to explain the photoresponse observed in amorphous oxides because electron traps are almost fully occupied and holes are strongly localized.\(^9,21\) In previous a-IGZO studies, \(^9\) and in studies of compositionally related amorphous Hf-In-Zn-O, \(^21\) it has been proposed that a more likely origin of photoinduced charge is the photoionization of oxygen vacancies in such films.\(^25\) All of the previous studies, however, analyzed their data with Laplace transform methods that either require a large number of fit parameters\(^9\) or introduce artificial discontinuities and spikes in the Laplace-transformed deduced density of states.\(^21\) The present study will demonstrate a useful method to characterize the full activation energy spectrum with only three fit parameters.

To study the time constant distribution and corresponding activation energy distribution associated with each photoconductivity curve, a stretched exponential fitting was employed, as it is common in other amorphous semiconductors.\(^15\) Photoconductivity curves following the stretched exponential function have the form:

\[
\sigma_{ph}(t) = \sigma_{ph,0} e^{-t/\tau}^{\beta},
\]

where \( \sigma_{ph,0} \) is the weighting amplitude, \( \tau \) is the effective time constant, and \( \beta \) is the stretching exponent. \( \tau \) can be defined as the time when the time-dependent photoconductivity \( \sigma_{ph}(t) \) relaxes to 1/e of its initial value \( \sigma_{ph,0} \). For accurate fitting of stretched exponentials, data should be taken at least to time \( t = \tau \).

Figure 4(a) illustrates unit norm stretched exponentials with various \( \beta \) values. When \( \beta = 1 \), Eq. (3) reduces to a simple exponential decay. When \( 0 < \beta < 1 \), the decay becomes “stretched” since a distribution of time constants are involved, with the shorter time constants causing a more rapid response for \( t < \tau \), and longer time-constants causing a slower response for \( t > \tau \). Larger \( \beta \) means a narrower

![FIG. 4. (a) The stretched exponential function simulates the photoresponse for \( \beta = 1, 0.75, 0.50, \) and 0.25, respectively. (b) Activation energy density distribution \( g_{ac} \) corresponding to the same \( \beta \) values. \( E_{ac} \) approximates the central value of the activation states calculated from Eq. (4). The left-right arrow indicates the activation energy full-width at half-maximum bandwidth \( \Delta_{ac} \). (c) Dependence of \( \Delta_{ac} \) on \( \beta \) values. Squares are calculated directly using inverse Laplace transform and the solid line is the empirical relation in Eq. (5). The inset shows how well the empirical fit matches the calculated energy bandwidths on a log-log scale.](image-url)
distribution of time constants around $\tau$. Conversely, smaller $\beta$ indicates a broader distribution of time constants.

Through Eq. (2), we can estimate the activation energy distribution from $\tau$ and $\beta$ values. A given time scale $t$ can be related to an activation energy $E$ by inverting Eq. (2)

$$E(t) = k_B T \ln(t/v).$$

(4)

The central moment $E_{ac} = E(\tau)$ of activation states is defined in terms of the stretched exponential time constant $\tau$. Correspondingly, $\beta$ characterizes the width of the distribution. Figure 4(b) shows the time constant distribution for several $\beta$ values, numerically calculated from the inverse Laplace transform of Eq. (3). When $\beta = 1$, the activation process is concentrated at a single energy level $E = E_{ac}$; when $\beta$ decreases, the activation energy expands to a wider band. The activation energy bandwidth $\Delta_{ac}$ is defined as the full width at half maximum of the distribution, identified in Fig. 4(b), increasing with decreasing $\beta$, as plotted in Fig. 4(c). The squares represent $\Delta_{ac}$ calculated directly from the inverse Laplace transform. A simple empirical equation

$$\Delta_{ac} = 4.6(\beta^{-0.81} - 1)k_B T$$

(5)

fits these calculated $\Delta_{ac}$ to within 8%, providing a quick way to estimate the activation energy bandwidth for any $\beta$ in the range $0.05 < \beta < 1$. The log-log inset to Fig. 4(c) illustrates the accuracy of Eq. (5).

To deduce the stretched exponential fitting parameters $\tau$ and $\beta$ from the experimental data, Eq. (3) can be rewritten as

$$\ln\left\{ -\ln \left[ \frac{\sigma_{ph}(t)}{\sigma_{ph0}} \right] \right\} = \beta \ln t - \beta \ln \tau.$$

(6)

Recalling that $\sigma_{ph}(t) = |\sigma(t) - \sigma_S|$ from Eq. (1), $\beta$, $\tau$, and $\sigma_S$ were determined using a least squares error line fit to Eq. (6). Each data point in the error estimate was weighted inversely proportional to the data density on the ln $t$ scale around that point.

Figure 5 shows an example of a stretched exponential fit to the photo-excitation data for the most semiconducting $P_{O_2} = 15$ mTorr sample at 300 K. The solid black curve indicates the best fit to the experimental data (gray squares). The dotted horizontal line in Fig. 5(a) is the asymptotic conductivity $\sigma_S$ which gives the least squares error. Such stretched exponential fits have been shown to be valid over month-long time scales in other amorphous materials.15,19,20 Thus, the excellent agreement to the fit here justifies extrapolating the stretched exponential beyond the measured data range by at least an order of magnitude as indicated with the grey lines.

The same analysis is applied to the dark relaxation transient photoconductivity, as illustrated in Fig. 6. For dark

![Figure 5](image-url)

**FIG. 5.** (a) Stretched exponential fit for the photo-excitation of the $P_{O_2} = 15$ mTorr sample at 300 K as a plot of conductivity $\sigma$ vs. time $t$. The horizontal dashed line illustrates the best fit for the asymptotic conductivity value $\sigma_S$. (b) The stretched exponential fit of Eq. (6). The squares are experimental data, and the solid black lines show the stretched exponential with the best fit parameters $\tau$, $\beta$, and $\sigma_S$ over the measured data range. Grey lines extrapolate the stretched exponential beyond the measured time scale.

![Figure 6](image-url)

**FIG. 6.** (a) Stretched exponential fit for the dark relaxation of the $P_{O_2} = 15$ mTorr sample at 300 K as a plot of conductivity $\sigma$ vs. time $t$. The horizontal dashed line at $\sigma_S = 0$ illustrates the expected asymptotic conductivity value for a lightly doped semiconducting sample. (b) The stretched exponential fit of Eq. (6). The squares are experimental data, and the black solid lines show the best fit parameters $\tau$, $\beta$, and $\sigma_S$ over the measured data range. Grey lines extrapolate the stretched exponential beyond the measured time scale. The vertical axis in (b) is the negative of that in Fig. 5(b) to highlight that this is a decay response.
relaxation, accurate fits are achieved under the approximation \( \sigma_t = 0 \), implying that the extrinsic doping is far less than the photoinduced carrier density for the time scales measured here. Note that the data could not be collected up to the time \( t = \tau \), but nonetheless the stretched exponential provides an accurate fit. The post-anneal data for illumination and relaxation were also fit to stretched exponential behavior. However, during the anneal cycle, both illuminated and dark curves failed to fit a stretched exponential lineshape because time dependent heating transients complicated the photoresponse. Table I lists the fitting results for as-grown and post-anneal data. For the \( P_{O_2} = 5 \text{ mTorr} \) post-anneal curves, the photoconductivity response did not exceed the measurement noise, so no conductivity change could be measured.

The activation energy distributions can now be calculated with inverse Laplace transforms of the stretched exponential fits. The results for the \( P_{O_2} = 15 \text{ mTorr} \) sample are plotted in Fig. 7. The height of the peaks can be normalized according to Eq. (1), since the total area under each density distribution curve is proportional to the total conductivity change \( \sigma_{ph,0} \) from \( t = 0 \) to \( \infty \)

\[
\sigma_{ph,0} = \sum_i \sigma_i = \int_0^\infty \sigma(\tau) d\tau \propto \int_{-\infty}^\infty g(E) dE.
\]

Here, \( \sigma(\tau) d\tau \) is the conductivity amplitude associated with a given \( \tau \) over the interval \( d\tau \), and \( g(E) \) is the density of activation states at energy \( E \).

The stretched exponential fit allows extrapolation of photoresponse to longer times and therefore larger energy ranges. Original experimental data were taken between \( t_{min} = 1 \text{ s} \) and \( t_{max} \approx 80,000 \text{ s} (1 \text{ day}) \). According to Eq. (4), the corresponding activation energy range is from \( E_{min} = E(t_{min}) = 0.77 \text{ eV} \) to \( E_{max} = E(t_{max}) = 1.06 \text{ eV} \), marked as the black segments of the distribution curves in Fig. 7.

The advantage of a stretched exponential fit is that it is valid up to month-long time scale in amorphous systems,\(^{15,19,20}\) thus, photoresponse at times shorter than \( t_{min} \) or longer than \( t_{max} \) can be extrapolated by at least an order of magnitude. One can therefore estimate the density distribution of activation energies over a broader range than what is directly measured. For the photo-excitation curve in Fig. 5(a) of the \( P_{O_2} = 15 \text{ mTorr} \) as-grown sample, this means that one can identify peak and expected linewidth of the density of activation states \( E_a \) and \( \Delta E_a \) is extrapolated by an order of magnitude in time makes it clear that the peak will lie at larger energies than for the illumination curve. Extrapolating further by several orders of magnitude allows one to predict

![FIG. 7. Activation energy density distributions for the \( P_{O_2} = 15 \text{ mTorr} \) sample, (a) as-grown and (b) post-anneal, deduced from inverse Laplace transforms of stretched exponential fits to the transient photoconductivity. Black segments of the curves correspond to the stretched exponential response over measured time scales. Gray curves correspond to an extrapolation of the stretched exponential behavior beyond the measured data. The gray arrows to the left of each peak indicate the time constant fit parameter \( \tau \) for each stretched exponential as measured on the top axis, or correspondingly the central moment \( E_a \) of the density of states on the bottom axis.](https://example.com/fig7)

| TABLE I. Stretched exponential fitting results. The \( \beta \), \( \tau \), and \( \sigma_t \) values are deduced from best fits to the data, and the energy scales for activated behavior \( E_a \) and \( \Delta E_a \) are derived from inverse Laplace transform analysis of these stretched exponentials. Following other authors, \( E_a \) was calculated assuming \( \nu = 10^{53} \text{ Hz} \).\(^{21,22}\) For \( P_{O_2} = 5 \text{ mTorr} \) sample, post-anneal photoconductivity was measured but the conductivity change was too small to perform stretched exponential analysis. |
| --- | --- | --- | --- | --- | --- |
| \( P_{O_2} \) | State | \( \beta \) | \( \tau \) (s) | \( \sigma_t \) (\( \Omega \text{ cm} \)\(^{-1} \)) | \( E_a \) (eV) | \( \Delta E_a \) (eV) | \( \beta \) | \( \tau \) (s) | \( \sigma_t \) (\( \Omega \text{ cm} \)\(^{-1} \)) | \( E_a \) (eV) | \( \Delta E_a \) (eV) |
| 5 mTorr | As-grown | 0.48 | 5.6 \times 10^4 | 8.0 | 1.05 | 0.10 | 0.46 | 4.5 \times 10^7 | 0 | 1.23 | 0.10 |
| 10 mTorr | As-grown | 0.46 | 1.1 \times 10^5 | 1.0 | 1.07 | 0.10 | 0.49 | 2.0 \times 10^6 | 0 | 1.15 | 0.09 |
| | Post-anneal | 0.66 | 2.4 \times 10^4 | 4.4 | 1.03 | 0.05 | 0.37 | 5.3 \times 10^9 | 0 | 1.35 | 0.14 |
| 15 mTorr | As-grown | 0.36 | 7.1 \times 10^4 | 1.8 | 1.06 | 0.15 | 0.53 | 1.4 \times 10^6 | 0 | 1.14 | 0.08 |
| | Post-anneal | 0.36 | 4.2 \times 10^3 | 1.1 | 1.11 | 0.15 | 0.47 | 4.4 \times 10^5 | 0 | 1.17 | 0.10 |
even the peak and linewidth of the dark relaxation density of activation states, though this result is more speculative. Values for the central moment activation energies $E_{ac}$ and linewidths $\Delta_{ac}$ derived in this manner are listed in Table I. Note that a direct measurement of the half maximum on the high energy tail of the illumination experiment would have required 2 weeks, and measurement of the same features in the dark relaxation curve would have required several months. Thus, the stretched exponential fit establishes a fast and reliable protocol for predicting the energy profile of deeply bound activation states.

It is worth noting that an accurate density of states profile requires proper estimation of the asymptotic conductivity $\sigma_S$. Due to the extremely slow response of the photoconductivity, the asymptotic conductivity cannot be simply assumed to be the initial dark value of the film conductivity as reported elsewhere, since full dark relaxation may take several months or more. The best way to assess the asymptotic value is with a time-dependent study and a stretched exponential line fit as described above. For all the films measured here, dark relaxation was always consistent with $\sigma_S = 0$. If one overestimates the dark conductivity or underestimates the saturation conductivity, the resulting energy distribution will be artificially cut off for energies greater than $E_{max}$.

One can determine accuracy of these fit parameters by varying the $\sigma_S$ value away from the optimal value and seeing how it affects the other parameters. For the data in Fig. 5, $\sigma_S$ can be varied from 1.5 to 2.5 ($\Omega$ cm)$^{-1}$ while keeping the least-squares error within twice the minimal value. This leads to an estimated accuracy of $E_{ac}$ to within 1.04 eV and 1.10 eV, and $\Delta_{ac}$ to within $\pm 0.2$ eV. Note that even assuming the smallest $\sigma_S$ and $\tau$, the sample would need 7 days to reach 95% of the asymptotic conductivity $\sigma_S$. Thus, it may be impractical to measure $\sigma_S$ directly by measuring for long times $t \gg \tau$, and the advantage of the error minimization method above to estimate $\sigma_S$ becomes clear, giving the same information in far less measurement time $t \sim \tau$.

From stretched exponential fit results shown in Table I and Fig. 7, we can see how the activation energy distribution changes with $P_O$, and measurement condition. Dark relaxation curves generally have larger effective activation energy $E_{ac}$ than those corresponding to photo-excitation curves by several $k_B T$, suggesting that excitation and recombination are distinct processes with recombination occurring through a more deeply bound activation process.

The stretched exponential analysis allows us to identify trends within the semiconducting $P_{O_2} = 15$ mTorr sample illustrated in Fig. 7. $E_{ac}$ shifted to higher energies after annealing, corresponding to slower photoresponse, as seen in the time response in Fig. 3. Also, the area under the density of states curve is reduced for dark relaxation compared to photo-excitation, suggesting that the effective number of active states is reduced in the dark. Finally, the post-anneal area of both curves is reduced, suggesting the important result that the number of photoactive states appears to go down after anneal. The same analysis can be applied to the other samples. Although no clear trends in $\beta$ or $\tau$ were observed as a function of oxygen pressure $P_{O_2}$ from this particular set of samples, the analysis method introduced here will permit more rapid and systematic characterizations. Future experiments with samples prepared at a finer resolution in oxygen pressure will be able to identify such trends.

**CONCLUSION**

In conclusion, we have studied transient photoconductivity response of a-IGZO thin films both under continuous illumination and in the dark. The magnitude of the photoresponse increases with increasing oxygen pressure of the deposited film. This photoconductivity is principally due to a photo-induced increase in carrier density, with mobility essentially constant during the photo-excitation or dark relaxation processes for each deposited sample. The photoresponse rates (for both excitation and relaxation) were enhanced when the sample was heated up to 350 K, but they were strongly suppressed upon returned to room temperature. It should therefore be possible to improve device stability by conducting a post-deposition thermal anneal at higher temperature.

Stretched exponential fitting was found to describe both the photo-excitation and dark relaxation curves, which provides a tool to study the energy distribution of activation processes. The stretched exponential fitting parameters $\tau$ and $\beta$ can be used to estimate the depth and width of the activation energy band, respectively. Different activation energies appear to be involved in the photo-excitation and dark relaxation transient photoconductivity.

The stretched exponential analysis offers new insight into the distribution of deeply bound energy states. It allows one to extrapolate the photoresponse over larger ranges of energy, revealing a peak in the density of states at deep energies and an estimation of the distribution linewidth. On the other hand, the direct Laplace transform method when applied to the raw data is susceptible to incorrect identification of the asymptotic $\sigma_S$, thereby erroneously cutting off the density of states at larger activation energies. With the stretched-exponential fitting technique presented here, transient photoconductivity analysis can be more efficiently characterized with fewer fit parameters, and with shorter measurement times than would be needed using standard Laplace transform analysis.

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