

## A Method and System For Determining Charge Carrier Lifetime

### FIELD OF INVENTION

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The present invention relates broadly to a method of determining charge carrier lifetime and a system for determining charge carrier lifetime.

### 10 BACKGROUND

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In semiconductor applications, charge carrier lifetime is the average time taken for an excess charge carrier to recombine. It is a significant parameter governing the performance of semiconductor devices. The charge carrier lifetime can determine factors such as switching speeds of diode and transistor devices, and energy conversion efficiency of solar cells and power output efficiency of light emitting diodes (LEDs). Therefore, to characterize the performance and quality of a semiconductor device, an accurate measurement of the charge carrier lifetime and its related parameters is typically desired.

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One method to measure the charge carrier lifetime is by creating excess charge carriers in a p-n junction device using an external excitation provided by a short forward current pulse and observing the open-circuit voltage decay of the device after the excitation source is terminated. This method, as introduced in B.R. Gossick, "On the Transient Behavior of Semiconductor Rectifiers," J. Appl. Phys., Vol. 26, no.11, p.1356, 1955, has since been found to be unreliable for estimating the charge carrier lifetime. The above finding is provided in John E. Mahan et.al., "Measurement of Minority Carrier Lifetime in Solar Cells from Photo-Induced Open-Circuit Voltage Decay," IEEE Transactions on Electron Devices, Vol. ED-26, No. 5 May 1979. John E. Mahan et.al. also describes another technique known as the Photo-Induced Open-Circuit Voltage Decay in which a light source (such as from a strobe lamp) is used as an excitation source for inducing an open circuit voltage across a p-n junction device. The charge carrier lifetime is then inferred from the open voltage decay profile. Such a method for measuring charge carrier lifetime typically involves a number of sequences starting from

creating excess carriers with an optical excitation source, observing the excess carriers recombination (or decaying) activities using instruments such as a microwave reflectometer, and extracting the lifetime parameters using mathematical fitting of the decaying signal profile.

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Although the technique in Mahan et.al. is arguably more accurate than the Gossick technique that uses forward current as the excitation source, the technique in Mahan et.al. possesses a number of limitations. Firstly, as light is the excitation source, the technique cannot be applied onto packaged devices since light cannot penetrate through the package material. Furthermore, it is typically difficult to observe the time decay signal profile exhibited by the excess carriers during the process of recombination through the packaged material. Thus, to measure device parameters via the photo-excitation technique would typically require the packages to be removed. This is not desirable as the test is typically meant to be non-destructive. In addition, the use of a light or photo-excitation source means that only the lifetime of charge carriers on device surfaces are being measured. It is typically not possible to investigate the bulk carriers since light does not penetrate into the devices. Further, the open voltage decay from which the charge carrier lifetime is typically inferred has a relatively fast discharge rate (that is, a relatively small RC time constant). Thus, the observation of the decay can typically only be performed within a short time span when the excess carriers recombine. As such, the decay profile can be considerably affected by the impedance or inherent capacitance of the measuring probes and instruments (such as an oscilloscope). This can in turn render the estimation of lifetime inaccurate. Further, the decay signal profile may also be affected by stored charge inherent in a p-n junction. The stored charge typically contributes further to the inaccuracy of the technique in Mahan et.al.

Currently, there have been proposed a number of different methods of determining charge carrier lifetime. For example, WO 2009/033629, US 6653, 850 and WO 01/04610 describe estimating charge carrier lifetime based on observing decay signal profiles from reflected microwaves. US 6982567 measures composition characteristics of a test device with an optical method for extracting charge carrier lifetime. Yet other methods use reflected radiofrequency signals, infra-red emissions or light-induced capacitance etc. to estimate charge carrier lifetime. In these methods, e.g. radiofrequency signals and infra-red emission are used for observing the recombination

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(decaying) profiles. However, optical light sources (e.g. a laser) are still required for carriers excitation. Such optical light typically do not penetrate through package materials. As for the light-induced capacitance technique, a highly sensitive capacitance sensor is required to be placed closely to the semiconductor surface for measurement.

5 Therefore, it will be appreciated that this technique is not suitable for packaged devices. These various methods are described in WO 2004/070775, EP 1413892, US 7045786, US6369603, US 5049816, US 5977788, US 6275060 and WO 00/60368.

Furthermore, there are currently commercially available equipment for measuring

10 charge carrier lifetimes. However, these equipment are primarily optimized to measure silicon wafers, ingots and boules, ie. not suitable for packaged devices. These equipment use techniques such as Quasisteady state photoconductance (QSSPC) which comprise using infra-red light as an excitation source and the lifetime is measured from a decay profile; or Transient Photoconductivity Decay (PCD) which comprise using

15 infra-red light as an excitation source and abruptly terminating the light. The decay of the photoconductance in darkness is monitored for measuring lifetime; or Charge Carrier Lifetime Photoluminescence (PL) imaging which comprise illuminating a sample area and capturing the photoluminescence emission with a camera for measuring charge carrier lifetime.

20 Hence, in view of the above, there exists a need for a method and system for determining charge carrier lifetime that seeks to address at least one of the above problems.

## 25 SUMMARY

In accordance with a first aspect of the present invention, there is provided a method of determining charge carrier lifetime, the method comprising the steps of

30 applying an excitation signal to a device; recording electrical 1/f noise exhibited by the device; and determining the charge carrier lifetime  $\tau$  of the device based on the recorded electrical 1/f noise;

wherein the step of determining the charge carrier lifetime may comprise recording two or more noise spectral of the device, each noise spectral being exhibited over a range of frequencies and at different applied excitation signals.

- 5 The method may further comprise modeling  $\tau$  as a function of operating current and noise frequency wherein the excitation signal is the operating current.

The method may comprise modeling  $\tau = \frac{D.I}{H(f).G(I)}$ , where D is a constant

- 10 which maintains unit consistency, H(f) and G(I) are functions of noise frequency f and operating current I respectively.

The method may further comprise using  $\tau = \frac{D.I}{H(f).G(I)}$  to derive a relationship

of  $\ln(S_f) = \ln(\alpha_H . e . G(I)) - \ln\left(\frac{f}{H(f)I D}\right)$  based on Hooge's noise

equation  $\frac{S_f(f)}{I^2} = \frac{\alpha_H}{f N_c}$  where  $S_f$  is the spectral power density of the noise, I is the

- 15 operating current,  $N_c$  is the total number of free charge carriers, f is the noise frequency and  $\alpha_H$  is a modelling parameter accounting for factors influencing bulk quality of the device.

- 20 The method may further comprise generating respective noise spectral representations of each recorded noise spectral corresponding to each different operating current I, each noise spectral representation comprising noise power spectral density as a function of frequency, and obtaining a noise gradient k and a y-axis intercept value  $C_0$  of each noise spectral representation.

- 25 The method may further comprise modeling  $H(f)/D = f^m$  where m is a current-dependent parameter and deriving m as a function of current I based on generating a representation of the noise gradient k as a function of the corresponding applied operating currents I.

The method may further comprise modeling  $G(I)$  based on generating a representation of the y-axis intercept value  $C_0$  as a function of the corresponding applied operating currents  $I$ .

5 The determination of the charge carrier lifetime  $\tau$  of the device may comprise using a weighted average value of  $\tau_{f_i}$  from the expression  $\frac{1}{\tau} = \frac{1}{N} \sum_{i=1}^N \frac{1}{\tau_{f_i}}$ , where  $N$  is a frequency range of each noise spectral sampled at an interval of 1 Hz.

The  $N$  may be from about 1 Hz to about 10kHz.

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The  $N$  may be from about 1 Hz to about 100Hz.

The method may further comprise modeling  $\tau$  as a function of operating current wherein the excitation signal is the operating current.

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The method may comprise modeling  $\tau = \frac{D \cdot I}{G(I)}$ , where  $D$  is a constant which maintains unit consistency and  $G(I)$  is a function of operating current  $I$ .

The method may further comprise using  $\tau = \frac{D \cdot I}{G(I)}$  to derive a relationship

20  $\ln(S_f) = \ln\left(\frac{\alpha_H \cdot e \cdot G(I)}{D}\right) - \ln(f)$  based on Hooge's noise equation  $\frac{S_f(f)}{I^2} = \frac{\alpha_H}{f N_c}$  where

$S_f$  is the spectral power density of the noise,  $I$  is the operating current,  $N_c$  is the total number of free charge carriers,  $f$  is the noise frequency and  $\alpha_H$  is a modelling parameter accounting for factors influencing bulk quality of the device.

25 The method may further comprise generating respective noise spectral representations of each recorded noise spectral corresponding to each different operating current  $I$ , each noise spectral representation comprising noise power

spectral density as a function of frequency, and obtaining a y-axis intercept value  $C_0$  of each noise spectral representation.

The method may further comprise modeling  $G(I)/D$  based on generating a representation of the y-axis intercept value  $C_0$  as a function of the corresponding applied operating currents  $I$ .

In the method, the charge carrier lifetime  $\tau$  of the device may be determined by using the maximum achievable  $\tau$  obtained under the different operating currents.

In accordance with a second aspect of the present invention, there is provided a system for determining charge carrier lifetime, the system comprising, an excitation source applying an excitation signal to a device; a signal analyzer for recording electrical  $1/f$  noise exhibited by the device; and a processor for determining the charge carrier lifetime of the device based on the recorded electrical  $1/f$  noise;

wherein the processor may determine the charge carrier lifetime by recording two or more noise spectral of the device, each noise spectral being exhibited over a range of frequencies and at different applied excitation signals.

The system may further comprise a shielded enclosure for shielding the device from electromagnetic interference.

The system may further comprise an amplifier coupled between an output of the device and the signal analyzer, the amplifier for amplifying the electrical noise.

The processor may determine the charge carrier lifetime by recording two or more noise spectral of the device, each noise spectral being exhibited over a range of frequencies and at different applied excitation signals.

The processor may model  $\tau$  as a function of operating current and noise frequency wherein the excitation signal is the operating current.

The processor may generate an expression  $\tau = \frac{D.I}{H(f).G(I)}$ , where  $D$  is a constant which maintains unit consistency,  $H(f)$  and  $G(I)$  are functions of noise frequency  $f$  and operating current  $I$  respectively.

The processor may use  $\tau = \frac{D.I}{H(f).G(I)}$  to derive a relationship of

$\ln(S_f) = \ln(\alpha_H . e . G(I)) - \ln\left(\frac{f}{H(f)/D}\right)$  based on Hooge's noise

equation  $\frac{S_f(f)}{I^2} = \frac{\alpha_H}{fN_c}$  where  $S_f$  is the spectral power density of the noise,  $I$  is the

operating current,  $N_c$  is the total number of free charge carriers,  $f$  is the noise frequency  
5 and  $\alpha_H$  is a modelling parameter accounting for factors influencing bulk quality of the device.

The processor may generate respective noise spectral representations of  
each recorded noise spectral corresponding to each different operating current  $I$ ,  
10 each noise spectral representation comprising noise power spectral density as a  
function of frequency, and obtaining a noise gradient  $k$  and a y-axis intercept value  
 $C_o$  of each noise spectral representation.

The processor may model  $H(f)/D = f^m$  where  $m$  is a current-dependent  
15 parameter and may derive  $m$  as a function of current  $I$  based on the processor  
generating a representation of the noise gradient  $k$  as a function of the  
corresponding applied operating currents  $I$ .

The processor may model  $G(I)$  based on the processor generating a  
20 representation of the y-axis intercept value  $C_o$  as a function of the corresponding  
applied operating currents  $I$ .

The processor may determine the charge carrier lifetime  $\tau$  of the device by  
using a weighted average value of  $\tau_{f_i}$  from the expression  $\frac{1}{\tau} = \frac{1}{N} \sum_{i=1}^N \frac{1}{\tau_{f_i}}$ , where  $N$  is a

25 frequency range of each noise spectral sampled at an interval of 1 Hz.

The  $N$  may be from about 1 Hz to about 10kHz.

The  $N$  may be from about 1 Hz to about 100Hz.

The processor may model  $\tau$  as a function of operating current wherein the excitation signal is the operating current.

- 5        The processor may generate an expression  $\tau = \frac{D.I}{G(I)}$ , where D is a constant which maintains unit consistency, and G(I) is a function of operating current I.

The processor may use  $\tau = \frac{D.I}{G(I)}$  to derive a relationship of

$$\ln(S_f) = \ln\left(\frac{\alpha_H \cdot e \cdot G(I)}{D}\right) - \ln(f) \text{ based on Hooge's noise equation } \frac{S_f(f)}{I^2} = \frac{\alpha_H}{f N_c} \text{ where } S_f$$

- 10    is the spectral power density of the noise, I is the operating current,  $N_c$  is the total number of free charge carriers, f is the noise frequency and  $\alpha_H$  is a modelling parameter accounting for factors influencing bulk quality of the device.

- 15    The processor may generate respective noise spectral representations of each recorded noise spectral corresponding to each different operating current I, each noise spectral representation comprising noise power spectral density as a function of frequency, and may obtain a y-axis intercept value  $C_o$  of each noise spectral representation.

- 20    The processor may model G(I)/D based on the processor generating a representation of the y-axis intercept value  $C_o$  as a function of the corresponding applied operating currents I.

- 25    The processor may determine the carrier lifetime  $\tau$  of the device by obtaining the maximum achievable  $\tau$  under the different operating currents.

- 30    In accordance with a third aspect of the present invention, there is provided a computer readable data storage medium having stored thereon computer code means for instructing a computer processor to execute a method of determining charge carrier lifetime, the method comprising the steps of applying an excitation signal to a

device; recording electrical  $1/f$  noise exhibited by the device; and determining the charge carrier lifetime of the device based on the recorded electrical  $1/f$  noise;

wherein the step of determining the charge carrier lifetime comprises recording two or more noise spectral of the device, each noise spectral being exhibited over a range of frequencies and at different applied excitation signals.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

Figure 1 is a schematic diagram illustrating a system for measuring charge carrier lifetime of a device in an example embodiment.

Figure 2 is a natural logarithmic graph of noise power spectral density (PSD) vs frequency for different operating currents measured from an example organic light emitting diode in an example embodiment.

Figure 3 is a graph of exponential function of the gradients of the noise spectral profiles in Fig. 2 plotted against corresponding current  $I$  of the noise spectral profiles in Figure 2.

Figure 4 is a graph of the logarithm values of electrical noise levels at  $1\text{Hz}$  obtained from the noise spectral profiles in Figure 2 plotted against corresponding current  $I$  of the noise spectral profiles in Figure 2.

Figure 5 is a schematic flowchart illustrating a method of determining charge carrier lifetime in an example embodiment.

Figure 6 is a schematic illustration of a computer system for implementing a method of determining charge carrier lifetime in an example embodiment.

Figure 7 is a graph of computed carrier lifetime versus operating current in an example embodiment.

**DETAILED DESCRIPTION**

An example embodiment can provide a system that can address the limitations of existing techniques that use light as an excitation source for inferring lifetime. In the example embodiment, charge carrier lifetime is inferred from a low frequency noise profile exhibited by a device during varying low current operations. As the example embodiment is based on electrical noise and not using light or optical sources for excitation, the example embodiment can be extended to packaged devices. Further, low frequency noise from a device can be acquired without significant distortion via a signal analyzer if there is an ohmic contact between the probe of the measurement unit and the device under test, and if the device is shielded from electro-magnetic interference (EMI).

Some portions of the description which follows are explicitly or implicitly presented in terms of algorithms and functional or symbolic representations of operations on data within a computer memory. These algorithmic descriptions and functional or symbolic representations are the means used by those skilled in the data processing arts to convey most effectively the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities, such as electrical, magnetic or optical signals capable of being stored, transferred, combined, compared, and otherwise manipulated.

Unless specifically stated otherwise, and as apparent from the following, it will be appreciated that throughout the present specification, discussions utilizing terms such as "scanning", "calculating", "determining", "replacing", "generating", "initializing", "outputting", or the like, refer to the action and processes of a computer system, or similar electronic device, that manipulates and transforms data represented as physical quantities within the computer system into other data similarly represented as physical quantities within the computer system or other information storage, transmission or display devices.

The present specification also discloses apparatus for performing the operations of the methods. Such apparatus may be specially constructed for the required purposes, or may comprise a general purpose computer or other device selectively activated or

reconfigured by a computer program stored in the computer. The algorithms and displays presented herein are not inherently related to any particular computer or other apparatus. Various general purpose machines may be used with programs in accordance with the teachings herein. Alternatively, the construction of more specialized  
5 apparatus to perform the required method steps may be appropriate. The structure of a conventional general purpose computer will appear from the description below.

In addition, the present specification also implicitly discloses a computer program, in that it would be apparent to the person skilled in the art that the individual  
10 steps of the method described herein may be put into effect by computer code. The computer program is not intended to be limited to any particular programming language and implementation thereof. It will be appreciated that a variety of programming languages and coding thereof may be used to implement the teachings of the disclosure contained herein. Moreover, the computer program is not intended to be limited to any  
15 particular control flow. There are many other variants of the computer program, which can use different control flows without departing from the spirit or scope of the invention.

Furthermore, one or more of the steps of the computer program may be performed in parallel rather than sequentially. Such a computer program may be stored  
20 on any computer readable medium. The computer readable medium may include storage devices such as magnetic or optical disks, memory chips, or other storage devices suitable for interfacing with a general purpose computer. The computer readable medium may also include a hard-wired medium such as exemplified in the Internet system, or wireless medium such as exemplified in the GSM mobile telephone system.  
25 The computer program when loaded and executed on such a general-purpose computer effectively results in an apparatus that implements the steps of the preferred method.

The invention may also be implemented as hardware modules. More particular, in the hardware sense, a module is a functional hardware unit designed for use with  
30 other components or modules. For example, a module may be implemented using discrete electronic components, or it can form a portion of an entire electronic circuit such as an Application Specific Integrated Circuit (ASIC). Numerous other possibilities exist. Those skilled in the art will appreciate that the system can also be implemented as a combination of hardware and software modules.

Figure 1 is a schematic diagram illustrating a system for determining charge carrier lifetime in a device in an example embodiment. The device can be a semiconductor or organic device. The determining is based on a low frequency electrical noise spectrum of the device when the device is driven under low current.

The system 100 comprises a grounded and EMI-shielded metallic enclosure 102. A device-under-test (DUT) 104 is placed in the enclosure 102 and connected to a low-noise excitation source 106. The excitation source 106 can be a current source. The excitation source 106 is used to drive the DUT 104. An output voltage generated by the DUT 104 for low frequency noise analysis is channelled (at 107) to a low-noise amplifier 108. The low-noise amplifier 108 is used for amplifying the DUT output voltage for low frequency noise analysis. A Digital Signal Analyzer (DSA) 110 is provided for acquiring the low frequency noise spectrum of the amplified voltage from the DUT 104 via the amplifier 108. A computing platform 112 is provided for performing mathematical analysis on the low frequency noise spectrum acquired by the DSA 110 and for extracting the charge carrier lifetime parameter of the DUT 104.

In the example embodiment, the charge carrier lifetime parameter is inferred from the electrical low-frequency noise spectrum (in logarithmic scale) exhibited by the DUT 104 when operated with a direct current provided by the source 106. The charge carrier lifetime is modelled as a function of noise frequency and operating current. The noise spectral density is modelled as a linear function of frequency, both parameters being computed in logarithmic scale. The charge carrier lifetime is inferred from a shift in the gradient of the noise spectral density in logarithmic scale under varying operating currents. More particularly, the charge carrier lifetime is inferred from a shift in the y-intercept of the noise spectral density in logarithmic scale under varying operating currents. The low frequency noise spectral density for charge carrier lifetime inferences is in the range from about 1 Hz to about 1000 Hz.

In an example embodiment, a measurement system is based on Hooge's Law, which states that the spectral noise power spectral follows the relationship:

$$\frac{S_I(f)}{I^2} = \frac{\alpha_H}{fN_c} \quad (1)$$

where  $S_i$  is the spectral power density of the noise,  $I$  is the operating forward current,  $N_c$  is the total number of free charge carriers, and  $f$  is the measuring noise frequency.  $\alpha_H$  is a modelling parameter that accounts for various factors influencing the bulk quality of the device.

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Hooge's equation is used in the example embodiment as the equation is an established model for describing 1/f noise which relates noise amplitude as a direct linear function of frequencies. The equation can, thus, be relatively easily interpreted and remodeled to explain experimental results. It will be appreciated that other noise models (such as Kleinpenning's model) can be traced back to the Hooge's equation.

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$N_c$  can be expressed in terms of the charge carrier lifetime  $\tau$  as follows:

$$N_c = \frac{I\tau}{e} \quad (2)$$

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where  $e$  is the electron charge.

The two abovementioned equations (1) and (2) can be combined to arrive at the following relationship:

$$S_i = \frac{\alpha_H \cdot I \cdot e}{f \cdot \tau} \quad (3)$$

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Thus, equation (3) allows an inference of the charge carrier lifetime  $\tau$  from the noise spectral associated with the frequency  $f$ .

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It will be appreciated that in the foregoing description, terms such as spectral power density of noise, noise power spectral density, noise spectrum and noise power spectral are used interchangeably to refer to  $S_i$ .

In natural logarithmic scale, equation (3) can be re-written as:

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$$\ln(S_i) = \ln(\alpha_H \cdot e \cdot I) - \ln(\tau) - \ln(f) \quad (4)$$

Figure 2 is a natural logarithmic graph of noise power spectral density (PSD) vs frequency for different operating currents measured from an example organic light emitting diode for illustrating the above relationship. From Figure 2, five different noise spectral profiles 201-205 are obtained for five different operating currents (ie. 200uA, 150uA, 100uA, 50uA and 20uA). In the example embodiment, as the test device is operated at low currents for a short duration (e.g. about 2 min), the test device is not degraded. Hence, the technique in the example embodiment can be non-destructive.

In the example embodiment, the frequency is measured from 1 Hz to 1kHz. As the system is based on 1/f noise spectrum, it will be appreciated that the model of the example embodiment is valid across the 1/f range typically measured from about 1 Hz to about 10kHz. However, it will be also appreciated that the measurement range can be narrowed substantially to from about 1 Hz to about 100 Hz for facilitating the computation of carrier lifetime based on smaller N wherein N is the frequency range of the noise spectral sampled at an interval of 1 Hz.

As for the current range, the current used in the example embodiment is in a range of about 0.3 uA to about 0.2 mA, ie. the current is sufficiently low enough to avoid significant degradation and heating of the test device.

Hence, in a theoretically ideal device, by plotting the noise power spectral  $S_f$  in natural logarithmic scale against frequency  $f$ , a gradient of -1, and a y-intercept that increases with the forward current can be obtained. However, the values of  $\tau$  can not be inferred directly from equation (4) due to the existence of another unknown parameter,  $\alpha_H$  in the y-intercept term.

In the example embodiment, to infer the value of  $\tau$ , the parameter  $\tau$  is remodelled as a function of  $I$  and  $f$ .

From Figure 2, it can be observed that as the current increases, the slope of the noise spectral becomes steeper and the y-intercept becomes larger. The inventors have recognised that the change in the charge carrier lifetime  $\tau$  due to current changes is significant in influencing the slope and the y-intercept (which reflects the low-frequency noise magnitude). That is, as  $\alpha_H$  is dependent on the bulk quality of the test device and

as the test device does not undergo significant degradation in the test procedure (compare Figure 2), the inventors have recognised that the bulk quality and hence,  $\alpha_H$ , remains substantially unchanged. In order to factor the effect of  $\tau$  on the noise spectral gradient and y-intercept, it is assumed that  $\tau$  is dependent on the forward current  $I$  and frequency  $f$  as follows:

$$\tau = \frac{D \cdot I}{H(f) \cdot G(I)} \quad (5)$$

where  $D$  is a constant which maintains the unit consistency of equation (5).  $H(f)$  and  $G(I)$  are functions of  $f$  and  $I$  respectively.

The remodelling of  $\tau$  in equation (5) allows the carrier lifetime  $\tau$  to influence the shift in the gradient and y-intercept of the noise power spectral (compare Figure 2). Combining equation (5) into equation (4) results in the following equation:

$$\ln(S_f) = \ln(\alpha_H \cdot e \cdot G(I)) - \ln\left(\frac{f}{H(f)/D}\right) \quad (6)$$

Based on the noise profiles 201-205 in Figure 2, the noise spectral density is in the general form of equation 7 under a constant current (e.g. 201 under current of 20uA).

$$\ln(S_f) = C_0 - k \ln(f) \quad (7)$$

where  $C_0$  is the logarithm value of  $S_f$  at a frequency of 1 Hz and  $k$  is the gradient term.

To model the influence of  $\tau$  on the noise gradient, a comparison between equations (6) and (7) shows that  $H(f)/D$  can take the form of  $H(f)/D = f^m$ . That is, the gradient of the noise spectral can be modeled via a parameter  $m$ , as shown in equation (8):

$$\ln(S_f) = \ln(\alpha_H \cdot e \cdot G(I)) - (1 - m) \ln(f) \quad (8)$$

It is noted that  $m$  is not a constant and is a parameter dependent on the driving current.

By comparing equation (7) and equation (8), it is inferred that

$$C_0 = \ln(\alpha_H \cdot e \cdot G(I)) \quad (9)$$

$$k = \frac{\Delta \ln(S_f)}{\Delta \ln(f)} = 1 - m \quad (10)$$

Therefore, in order to obtain carrier lifetime  $\tau$ ,  $k$  and  $G(I)$  are identified separately.

It can be observed from the noise spectral (compare Figure 2) that the noise gradient  $k$  increases with the driving or operating current. Thus,  $m$  can be modeled as a function of current  $I$ .

Figure 3 is a graph of exponential function of the gradients of the noise spectral profiles in Fig. 2 plotted against corresponding current  $I$  of the noise spectral profiles in Figure 2.

By plotting the exponential function values of gradient  $k$  versus  $I$ , the relationship between the gradient  $k$  and current  $I$  is deduced to be

$$k = \ln(k_0 \cdot I + c) \quad (11)$$

where  $k_0$  is the gradient and  $c$  is the Y-intercept of the linear graph 302 in Figure 3.

From graph 302, the following values can be identified:

$$c = 2.465$$

$$k_0 = 13756$$

Since  $k = 1 - m$  (see equation (10)) ie.  $m = 1 - k$ ,  $H(f)/D = f^m$  can be further established using equation (11) as:

$$\frac{H(f)}{D} = f^{1 - \ln(k_0 I + c)} \quad (12)$$

From equation (9), it is shown that:

$$C_0 = \ln(\alpha_H \cdot e \cdot G(I))$$

$$\text{Therefore, } C_0 = \ln(\alpha_H \cdot e) + \ln(G(I)) \quad (13)$$

5 where, as established at equation (7),  $C_0$  is logarithm value of the electrical noise level at 1Hz.

10 Figure 4 is a graph of the logarithm values of the electrical noise level at 1Hz of the noise spectral profiles in Figure 2 plotted against corresponding currents  $I$  of the noise spectral profiles.

By plotting  $C_0$  against current  $I$ , it can be observed that the two parameters form a linear relationship (see linear graph 402 in Figure 4).

15 Based on graph 402, a linear equation can be obtained as follows :

$$C_0 = \beta I + P \quad (14)$$

where  $\beta = 49052.1$  (gradient of graph 402) and  $P = -24.7$  (y-intercept of graph 402)

20 Hence, from equations (13) and (14), it can be shown that

$$G(I) = \exp(\beta I) \quad (15)$$

$\beta$  is the proportionality between  $C_0$  and  $I$ , which can be obtained from the gradient of the graph 402 in Figure 4.

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Using equations (3), (5), (15) and  $H(f)/D = f^m$ , the following equations are obtained:

$$S_I = \frac{\alpha_H \cdot I \cdot e}{f \cdot \tau} = \frac{\alpha_H \cdot e \cdot H(f) \cdot G(I)}{D \cdot f} \quad (16)$$

$$S_I = \alpha_H \cdot e \cdot f^{m-1} \cdot \exp(\beta \cdot I) \quad (17)$$

$$30 \quad \ln(S_I) = [\ln(\alpha_H \cdot e) + \beta \cdot I] - (1 - m) \ln f \quad (18)$$

Equation (17) indeed satisfies the general 1/f behavior and describes the 1/f noise spectra well. Therefore, the example embodiment is mathematically sound. In other words, the equation (17) describes the 1/f noise behavior well as it has accounted for the observation that both the noise gradient and magnitude increases with operating current. The noise magnitude (at 1 Hz) is represented by  $(\ln(\alpha_H e) + \beta I)$ , while the noise gradient is represented by  $(1-m)$  where m is a current dependent parameter.

Based on equation (5), (12) and (15), the following  $\tau$  equation is obtained:

$$\tau = \frac{I}{f^{1-\ln(\lambda_0 I + c)} \cdot \exp(\beta I)} \quad (19)$$

In equation (3),  $S_f = \frac{\alpha_H \cdot I \cdot e}{f \cdot \tau}$ , where  $S_f$  is the low frequency noise (LFN) at all frequencies ranging from 1-100Hz and  $\tau$  is the charge carrier lifetime associated with frequency f in an electrical device (e.g. DUT 104 of Figure 1).

Thus, from equation (3), it can be proposed that:

$$\frac{S_f}{I} \cdot f \propto \frac{1}{\tau} \quad (20)$$

In the example embodiment, calculating the charge carrier lifetime  $\tau$  depends on the frequency. Therefore, at each specific frequency  $f_i$ , the corresponding carrier lifetime at frequency  $f_i$  can be written as:

$$\frac{S_{f_i}}{I} \cdot f_i = \frac{\alpha_H e}{\tau_{f_i}} \quad (21)$$

In other words, the model in the example embodiment suggests that charge carriers of a specific lifetime  $\tau_i$  contribute to a noise frequency  $f_i$ . Therefore, to determine the average lifetime  $\tau$ , the noise spectral over a low frequency spectrum (about 1 Hz to about 100 Hz) can be integrated as seen below:

19

$$\sum_{i=1}^N \frac{S_{i,f_i}}{I} \cdot f_i = \sum_{i=1}^N \frac{\alpha_H \cdot e}{\tau_{f_i}} = \frac{N \cdot \alpha_H \cdot e}{\tau} \quad (22)$$

Therefore, from equation (22), a relationship is obtained as:

$$\sum_{i=1}^N \frac{1}{\tau_{f_i}} = \frac{N}{\tau} \quad (23)$$

5 where N is the frequency range of the noise spectral sampled at an interval of 1 Hz.

From equation (19), where  $\tau = \frac{I}{f^{1-\ln(k_0 I + c)} \cdot \exp(\beta \cdot I)}$ , the specific frequency charge carrier lifetime  $\tau_{f_i}$  can be derived as

$$\tau_{f_i} = \frac{I}{f_i^{1-\ln(k_0 I + c)} \cdot \exp(\beta \cdot I)} \quad (24)$$

10 Thus, by combining equations (24) and (23), the effective charge carrier lifetime can be derived as follows:

$$\frac{N}{\tau} = \sum_{i=1}^N \frac{1}{\tau_{f_i}} = \sum_{i=1}^N \frac{f_i^{1-\ln(k_0 I + c)} \cdot \exp(\beta \cdot I)}{I} \quad (25)$$

$$\tau = \frac{N}{\sum_{i=1}^N \left( \frac{f_i^{1-\ln(k_0 I + c)} \cdot \exp(\beta \cdot I)}{I} \right)} \quad (26)$$

15 In the example embodiment, the parameters c,  $k_0$  and  $\beta$  are derived for each new DUT. Thus, the technique of the example embodiment can be used as a direct measurement of charge carrier lifetime.

20 Experiments have been conducted on different devices to test validity of the described example embodiment in charge lifetime computation. Table 1 below tabulates the computed carrier lifetimes at corresponding operating currents and measurement range N. It can be observed that the results are consistent with theoretical values reported in literature.

| Devices Types | Operating | Computed Carrier Lifetime (s) | Reported |
|---------------|-----------|-------------------------------|----------|
|---------------|-----------|-------------------------------|----------|

|                                        | Current ( $\mu\text{A}$ ) | N=100      | N=200      | N=300      | Values from Literature (s) |
|----------------------------------------|---------------------------|------------|------------|------------|----------------------------|
| OLED                                   | 20                        | 2.37969E-6 | 2.41203E-6 | 2.41564E-6 | $\sim 10^{-6}$             |
|                                        | 50                        | 5.63680E-6 | 5.56456E-6 | 5.57012E-6 |                            |
|                                        | 100                       | 2.99957E-6 | 3.03234E-6 | 3.05634E-6 |                            |
|                                        | 150                       | 7.58469E-7 | 7.54432E-7 | 7.54354E-7 |                            |
|                                        | 200                       | 1.40718E-7 | 3.54343E-7 | 3.56449E-7 |                            |
| Si Thin Film Solar Cell                | 0.30                      | 1.57268E-5 | 6.13519E-6 | 8.67672E-6 | $\sim 10^{-4} - 10^{-6}$   |
|                                        | 0.50                      | 2.50343E-5 | 1.38555E-5 | 9.8154E-6  |                            |
|                                        | 1.55                      | 6.09154E-5 | 3.4298E-5  | 2.4545E-5  |                            |
|                                        | 5.20                      | 8.66368E-5 | 5.2227E-5  | 3.89201E-5 |                            |
|                                        | 7.20                      | 7.37646E-5 | 4.65043E-5 | 3.55913E-5 |                            |
| Dye-sensitized solar cell              | 1                         | 5.52341E-6 | 3.53445E-6 | 2.72916E-6 | $\sim 10^{-6}$             |
|                                        | 1.65                      | 3.86833E-6 | 1.13181E-6 | 5.51523E-7 |                            |
|                                        | 2.15                      | 1.80795E-6 | 4.49732E-7 | 1.993E-7   |                            |
| P3HT/PCBM Solar Cell                   | 0.82                      | 5.3432E-6  | 3.3249E-6  | 1.22233E-6 | $\sim 10^{-6}$             |
|                                        | 1.5                       | 6.3534E-6  | 4.6726E-6  | 2.24812E-6 |                            |
|                                        | 2.5                       | 7.6587E-6  | 5.9876E-6  | 3.77672E-6 |                            |
|                                        | 3                         | 8.1237E-6  | 6.7625E-6  | 4.55002E-6 |                            |
| BiFeO <sub>3</sub> /SrTiO <sub>3</sub> | 0.4                       | 4.12656E-4 | 4.11631E-4 | 4.1124E-4  | $\sim 10^{-6}$             |
|                                        | 0.5                       | 6.43686E-4 | 6.40305E-4 | 6.38972E-4 |                            |
|                                        | 1                         | 0.00193    | 0.00188    | 0.00186    |                            |
|                                        | 1.5                       | 0.00272    | 0.0026     | 0.00254    |                            |
|                                        | 1.98                      | 0.00286    | 0.00266    | 0.00256    |                            |

Table 1

In Table 1, N represents the measurement ranges 1-100Hz (N=100), 1-200Hz (N=200) and 1-300Hz (N=300) for the different devices.

5

It will be appreciated that, theoretically, a larger N value produces a more accurate result as the effects from charge carriers contributing to a wider noise spectrum are considered. However, it has been observed that the noise amplitude relating to higher frequencies is much lower than that at lower frequencies.

10 Therefore, the inventors have recognised that the higher frequency end of the noise spectral can be ignored by assuming that the charge carriers contributing to high frequency noise is negligible. In the experiments for Table 1, it has been observed that the computed charge lifetime stays substantially within the same order for N = 100, 200 and 300. This indicates that the frequency range is sufficient to yield an  
 15 accurate measurement of the lifetime. It will be appreciated that the N values are selectable by a user such that the user can set a smaller value to facilitate the computation.

Thus, the inventors have recognised that as long as the computed results in Table 1 do not exhibit large changes (e.g. a change in the order of 10) upon increasing the measurement range, it can be concluded that a sufficiently high value of N has been used.

Thus, based on the above, Table 1 provides a set of the charge carrier lifetimes under different currents. A user may choose the lifetime corresponding to a typical (or minimum) operating current of a device as the relevant lifetime parameter. Alternatively, the user can use the average value of the computed lifetimes for a device measured over a range of operating currents. For estimation of recombination lifetime, the user may choose the maximum achievable lifetime for a device measured over a range of operating currents.

The inventors have recognised that in many cases, the change in the noise gradient is small under varying forward current conditions, and the value of  $\tau$  is largely influenced by the operating current.

Therefore, in another example embodiment, the algorithm for determining charge carrier lifetime can be simplified by modelling  $\tau$  as a function of operating current only (contrast to equation (5)). This leads to a modelling equation of:

$$\tau = \frac{D \cdot I}{G(I)} \quad (27)$$

Substituting equation (27) into Hooge's Equation (see equation (4)), the noise spectral density can be expressed as:

$$\ln(S_f) = \ln\left(\frac{\alpha_H \cdot e \cdot G(I)}{D}\right) - \ln(f) \quad (28)$$

Comparing equation (28) with equation (7),

$$C_0 = \ln\left(\frac{\alpha_H \cdot e \cdot G(I)}{D}\right) \quad (29)$$

or

$$C_0 = \ln(\alpha_H \cdot e) + \ln(G(I) / D) \quad (30)$$

5

Based on Figure 4 and equation (14), it can be derived that

$$G(I) / D = \exp(\beta I) \quad (31)$$

where  $\beta = 49052.1$  (gradient of graph 402)

10

Therefore, from equations (31) and (27), the value of  $\tau$  under different operating currents can be derived in the following expression:

$$\tau = \frac{I}{\exp(\beta I)} \quad (32)$$

15

As recombination lifetime is typically measured under open circuit conditions, it tends to be the longest achievable duration that a free charge carrier can exist in a material. Therefore, the maximum achievable  $\tau$  in equation (32) under different currents is taken to be an estimation of the recombination lifetime.

20

Figure 7 is a graph of computed carrier lifetime versus operating current in an example embodiment. The graph 702 is based on the model  $\tau = \frac{D \cdot I}{G(I)}$  the plot from

Figure 4 pertaining to an example organic light emitting diode and equation (32). The recombination lifetime can be derived from the peak 704 of the graph 702 of the

25

Figure 5 is a schematic flowchart 500 illustrating a method of determining charge carrier lifetime in an example embodiment. At step 502, an excitation signal is applied to a device. At step 504, electrical noise exhibited by the device is recorded.

At step 506, the charge carrier lifetime of the device is determined based on the recorded electrical noise.

In one example embodiment, the charge carrier lifetime  $\tau$  of a device is modelled as a function of operating current and noise frequency. In the example embodiment, the model can adopt the form  $\tau = \frac{D.I}{H(f).G(I)}$ .

The  $\tau$  model can be substituted into Hooge's noise equation to form a relationship  $\ln(S_f) = \ln(\alpha_H . e . G(I)) - \ln\left(\frac{f}{H(f)/D}\right)$ .

The sub-functions in the  $\tau$  model,  $H(f)$  and  $G(I)$  are then separately identified based on observing the change in the gradient ( $k$ ) and y-intercept at 1 Hz ( $C_0$ ) of noise spectral (in logarithmic scale) respectively as operating current  $I$  applied to the device varies.

For identification of  $H(f)/D$ , the sub-function  $H(f)/D$  is modeled as a function dependent on  $f^m$ , where  $m$  is a current-dependent parameter. The expression of  $m$  as a function of current  $I$  is then identified by curve-fitting on a graph of noise gradient  $k$  versus current  $I$ . The derived expression can be  $\frac{H(f)}{D} = f^{1-\ln(k_0/c)}$ .

For identification of  $G(I)$ , the expression of sub-function  $G(I)$  is identified by curve-fitting on a graph of y-intercept at 1 Hz,  $C_0$ , versus current  $I$ . In the example embodiment,  $G(I) = \exp(\beta I)$ .

Upon establishing the expressions for  $H(f)/D$  and  $G(I)$ , the lifetime of the carrier contributing to each noise frequency  $f$  of the noise spectral under an operating current  $I$  is obtained. In the example embodiment, the resulting charge carrier lifetime for each frequency is  $\tau_f = \frac{I}{f^{1-\ln(k_0/c)} . \exp(\beta I)}$ . The average charge carrier lifetime,  $\tau$ , is computed by taking the average of  $\tau_f$ . In the example embodiment, the average lifetime

is computed from  $\frac{1}{\tau} = \frac{1}{N} \sum_{i=1}^N \frac{1}{\tau_{f_i}}$  where N is the frequency range of the noise spectral sampled at an interval of 1 Hz.

In another example embodiment, a simplified model of  $\tau = \frac{D.I}{G(I)}$  is adopted,

5 so as to derive the relationship  $\ln(S_f) = \ln\left(\frac{\alpha_H \cdot e \cdot G(I)}{D}\right) - \ln(f)$

The sub-functions in the  $\tau$  model,  $G(I)/D$ , are then separately identified based on observing the change in the y-intercept at 1 Hz ( $C_0$ ) of the noise spectral (in logarithmic scale) respectively as operating current I applied to the device varies. The expression of  
10 sub-function  $G(I)/D$  is identified by curve-fitting on a graph of y-intercept at 1 Hz,  $C_0$ , versus current I. In the example embodiment,  $G(I)/D = \exp(\beta I)$ .

Upon establishing the expressions for  $G(I)/D$ , the lifetime of the carrier can be estimated from the maximum achievable  $\tau$  under varying operating currents.

15

The inventors have recognised that there are no known reports that have succeeded (or even attempted) in extracting charge carrier lifetime from low frequency electrical noise profiles. The inventors have also recognised that a low frequency noise model represented by Hooge's equation may contain unknown parameters that are  
20 relatively difficult to quantify.

The example embodiments have modelled the charge carrier lifetime as a function of frequency and current that can facilitate extraction of the lifetime parameter from Hooge's equation.

25

The inventors have also recognised that the model of charge carrier lifetime can be simplified so that it is a function of forward current only.

In the described example embodiments, measurements on a device-under-test  
30 can be carried out whether or not the device is packaged or unpackaged since the

measurements do not require projecting irradiance on the device to create excess charge carriers.

Further, the example embodiments do not require observing open-circuit voltage decay that mirrors excess carrier recombination activities. Rather, the example  
5 embodiments can analyze low frequency noise spectral profiles of the device for extracting the charge lifetime of carriers. The low frequency noise behavior can be acquired without significant distortion if the measurement set-up is appropriately shielded from external EMI. Further, the noise profile can be monitored continuously  
10 over a period of time (ie. not within a short observation period).

In addition, the example embodiments use relatively simpler equipment and steps for acquiring electrical noise profiles under varying operating currents and extracting the lifetime parameters.

Further, the example embodiments can develop a portable test platform for qualifying semiconductor devices based on effective charge carrier lifetime without using light excitation sources. The platform can be useful for packaged or encapsulated devices as light cannot penetrate the packaged material. With  
20 electrical excitation, the platform enables the lifetime of both the bulk and surface carriers of the test devices to be measured. Further, the example embodiments can provide a relatively quick and cost-effective method to grade electronic gadgets such as solar cells and LCD panels. In addition, the example embodiments can provide a quality control station for monitoring the charge carrier lifetime throughout  
25 a solar cell manufacturing process. Such a station can provide valuable information on the influence of individual processing steps on the device performance. For illustration, it will be appreciated that the effective charge carrier lifetime ( $\tau_{eff}$ ) is one significant material parameter that can affect the efficiency of a Si solar cell. It can determine whether photogenerated carriers can reach the junction of a cell and contribute to the current of the cell. It can also determine the upper limit for a voltage that  
30 a solar cell can generate. Thus, by monitoring the variation of the charge carrier lifetime throughout the solar cell manufacturing process, valuable information about the influence of individual processing steps on the charge carrier lifetime and subsequently, on device performance can be obtained. The example embodiments can thus provide a

robust technique to be employed and installed on a manufacturing line of Si wafers and Si solar cells.

The method and system of the example embodiment can be implemented on a computer system 600, schematically shown in Figure 6. It may be implemented as software, such as a computer program being executed within the computer system 600, and instructing the computer system 600 to conduct the method of the example embodiment.

The computer system 600 comprises a computer module 602, input modules such as a keyboard 604 and mouse 606 and a plurality of output devices such as a display 608, and printer 610.

The computer module 602 is connected to a computer network 612 via a suitable transceiver device 614, to enable access to e.g. the Internet or other network systems such as Local Area Network (LAN) or Wide Area Network (WAN). The computer module 602 in the example includes a processor 618, a Random Access Memory (RAM) 620 and a Read Only Memory (ROM) 622. The computer module 602 also includes a number of Input/Output (I/O) interfaces, for example I/O interface 624 to the display 608, and I/O interface 626 to the keyboard 604.

The components of the computer module 602 typically communicate via an interconnected bus 628 and in a manner known to the person skilled in the relevant art.

The application program is typically supplied to the user of the computer system 600 encoded on a data storage medium such as a CD-ROM or flash memory carrier (e.g. a USB thumb drive) and read utilising a corresponding data storage medium drive of a data storage device 630. The application program is read and controlled in its execution by the processor 618. Intermediate storage of program data maybe accomplished using RAM 620.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific

embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

# CLAIMS

1. A method of determining charge carrier lifetime, the method comprising the steps of:  
applying an excitation signal to a device;  
recording electrical 1/f noise exhibited by the device; and  
determining the charge carrier lifetime  $\tau$  of the device based on the recorded electrical 1/f noise;

wherein the step of determining the charge carrier lifetime comprises recording two or more noise spectral of the device, each noise spectral being exhibited over a range of frequencies and at different applied excitation signals.

2. The method as claimed in claim 1, further comprising modeling  $\tau$  as a function of operating current and noise frequency wherein the excitation signal is the operating current.

3. The method as claimed in claim 2, wherein  $\tau = \frac{DI}{H(f).G(I)}$ , where D is a constant which maintains unit consistency, H(f) and G(I) are functions of noise frequency f and operating current I respectively.

4. The method as claimed in claim 3, further comprising using  $\tau = \frac{DI}{H(f).G(I)}$  to derive a relationship of  $\ln(S_1) = \ln(\alpha_H . e . G(I)) - \ln\left(\frac{f}{H(f)/D}\right)$  based on Hooge's noise equation  $\frac{S_1(f)}{I^2} = \frac{\alpha_H}{fN_c}$  where  $S_1$  is the spectral power density of the noise, I is the operating current,  $N_c$  is the total number of free charge carriers, f is the noise frequency and  $\alpha_H$  is a modelling parameter accounting for factors influencing bulk quality of the device.

5. The method as claimed in claim 4, further comprising generating respective noise spectral representations of each recorded noise spectral corresponding to each different operating current I, each noise spectral

representation comprising noise power spectral density as a function of frequency, and obtaining a noise gradient  $k$  and a y-axis intercept value  $C_0$  of each noise spectral representation.

6. The method as claimed in claim 5, further comprising modeling  $H(f)/D = f^m$  where  $m$  is a current-dependent parameter and deriving  $m$  as a function of current  $I$  based on generating a representation of the noise gradient  $k$  as a function of the corresponding applied operating currents  $I$ .

7. The method as claimed in claim 5, further comprising modeling  $G(I)$  based on generating a representation of the y-axis intercept value  $C_0$  as a function of the corresponding applied operating currents  $I$ .

8. The method as claimed in claims 2 or 3, wherein the determining of the charge carrier lifetime  $\tau$  of a device comprises using a weighted average value of  $\tau_{f_i}$  from the expression  $\frac{1}{\tau} = \frac{1}{N} \sum_{i=1}^N \frac{1}{\tau_{f_i}}$ , where  $N$  is a frequency range of each noise spectral sampled at an interval of 1 Hz.

9. The method as claimed in claim 8, wherein the  $N$  is from about 1 Hz to about 10kHz.

10. The method as claimed in claim 9, wherein the  $N$  is from about 1 Hz to about 100Hz.

11. The method as claimed in claim 1, further comprising modeling  $\tau$  as a function of operating current wherein the excitation signal is the operating current.

12. The method as claimed in claim 11, wherein  $\tau = \frac{DJ}{G(I)}$ , where  $D$  is a constant which maintains unit consistency and  $G(I)$  is a function of operating current  $I$ .

13. The method as claimed in claim 12, further comprising using  $\tau = \frac{DI}{G(I)}$  to derive a relationship of  $\ln(S_f) = \ln\left(\frac{\alpha_H \cdot e \cdot G(I)}{D}\right) - \ln(f)$  based on Hooge's noise equation  $\frac{S_f(f)}{I^2} = \frac{\alpha_H}{fN_c}$  where  $S_f$  is the spectral power density of the noise,  $I$  is the operating current,  $N_c$  is the total number of free charge carriers,  $f$  is the noise frequency and  $\alpha_H$  is a modelling parameter accounting for factors influencing bulk quality of the device.

14. The method as claimed in claim 13, further comprising generating respective noise spectral representations of each recorded noise spectral corresponding to each different operating current  $I$ , each noise spectral representation comprising noise power spectral density as a function of frequency, and obtaining a y-axis intercept value  $C_0$  of each noise spectral representation.

15. The method as claimed in claim 14, further comprising modeling  $G(I)/D$  based on generating a representation of the y-axis intercept value  $C_0$  as a function of the corresponding applied operating currents  $I$ .

16. The method as claimed in claims 11 or 12, wherein the carrier lifetime  $\tau$  of the device is determined using the maximum achievable  $\tau$  obtained under the different operating currents.

17. A system for determining charge carrier lifetime, the system comprising,

an excitation source applying an excitation signal to a device;

a signal analyzer for recording electrical  $1/f$  noise exhibited by the device;

and

a processor for determining the charge carrier lifetime of the device based on the recorded electrical  $1/f$  noise;

wherein the processor determines the charge carrier lifetime by recording two or more noise spectral of the device, each noise spectral being exhibited over a range of frequencies and at different applied excitation signals.

18. The system as claimed in claim 17, further comprising a shielded enclosure for shielding the device from electromagnetic interference.

19. The system as claimed in claims 17 or 18, further comprising an amplifier coupled between an output of the device and the signal analyzer, the amplifier for amplifying the electrical noise.

20. The system as claimed in any one of claims 17 to 19, wherein the processor models  $\tau$  as a function of operating current and noise frequency wherein the excitation signal is the operating current.

21. The system as claimed in claim 20, wherein the processor generates an expression  $\tau = \frac{DI}{H(f).G(I)}$ , where D is a constant which maintains unit consistency, H(f) and G(I) are functions of noise frequency f and operating current I respectively.

22. The system as claimed in claim 21, wherein the processor uses  $\tau = \frac{DI}{H(f).G(I)}$  to derive a relationship of  $\ln(S_i) = \ln(\alpha_H . e . G(I)) - \ln\left(\frac{f}{H(f)/D}\right)$  based on Hooge's noise equation  $\frac{S_i(f)}{I^2} = \frac{\alpha_H}{fN_c}$  where  $S_i$  is the spectral power density of the noise, I is the operating current,  $N_c$  is the total number of free charge carriers, f is the noise frequency and  $\alpha_H$  is a modelling parameter accounting for factors influencing bulk quality of the device.

23. The system as claimed in claim 22, wherein the processor generates respective noise spectral representations of each recorded noise spectral corresponding to each different operating current I, each noise spectral representation comprising noise power spectral density as a function of frequency, and obtaining a noise gradient k and a y-axis intercept value  $C_0$  of each noise spectral representation.

24. The system as claimed in claim 23, wherein the processor models  $H(f)/D = f^m$  where  $m$  is a current-dependent parameter and derives  $m$  as a function of current  $I$  based on the processor generating a representation of the noise gradient  $k$  as a function of the corresponding applied operating currents  $I$ .

25. The system as claimed in claim 23, wherein the processor models  $G(I)$  based on the processor generating a representation of the y-axis intercept value  $C_0$  as a function of the corresponding applied operating currents  $I$ .

26. The system as claimed in claims 20 or 21, wherein the processor determines the charge carrier lifetime  $\tau$  of the device by using a weighted average value of  $\tau_{f_i}$  from the expression  $\frac{1}{\tau} = \frac{1}{N} \sum_{i=1}^N \frac{1}{\tau_{f_i}}$ , where  $N$  is a frequency range of each noise spectral sampled at an interval of 1 Hz.

27. The system as claimed in claim 26, wherein the  $N$  is from about 1 Hz to about 10kHz.

28. The system as claimed in claim 27, wherein the  $N$  is from about 1 Hz to about 100Hz.

29. The system as claimed in any one of claim 17 to 28, wherein the processor models  $\tau$  as a function of operating current wherein the excitation signal is the operating current.

30. The system as claimed in claim 29, wherein the processor generates an expression  $\tau = \frac{DI}{G(I)}$ , where  $D$  is a constant which maintains unit consistency, and  $G(I)$  is a function of operating current  $I$ .

31. The system as claimed in claim 30, wherein the processor uses  $\tau = \frac{DI}{G(I)}$  to derive a relationship of  $\ln(S_f) = \ln\left(\frac{\alpha_H \cdot e \cdot G(I)}{D}\right) - \ln(f)$  based on Hooge's

noise equation  $\frac{S_f(f)}{I^2} = \frac{\alpha_H}{fN_c}$  where  $S_f$  is the spectral power density of the noise,  $I$  is the operating current,  $N_c$  is the total number of free charge carriers,  $f$  is the noise frequency and  $\alpha_H$  is a modelling parameter accounting for factors influencing bulk quality of the device.

32. The system as claimed in claim 31, wherein the processor generates respective noise spectral representations of each recorded noise spectral corresponding to each different operating current  $I$ , each noise spectral representation comprising noise power spectral density as a function of frequency, and obtains a y-axis intercept value  $C_0$  of each noise spectral representation.

33. The system as claimed in claim 32, wherein the processor models  $G(I)/D$  based on the processor generating a representation of the y-axis intercept value  $C_0$  as a function of the corresponding applied operating currents  $I$ .

34. The system as claimed in claims 29 or 30, wherein the processor determines the carrier lifetime  $\tau$  of the device by obtaining the maximum achievable  $\tau$ , under the different operating currents.

35. A computer readable data storage medium having stored thereon computer code means for instructing a computer processor to execute a method of determining charge carrier lifetime, the method comprising the steps of:

- applying an excitation signal to a device;
- recording electrical  $1/f$  noise exhibited by the device; and
- determining the charge carrier lifetime of the device based on the recorded electrical  $1/f$  noise;

wherein the step of determining the charge carrier lifetime comprises recording two or more noise spectral of the device, each noise spectral being exhibited over a range of frequencies and at different applied excitation signals.