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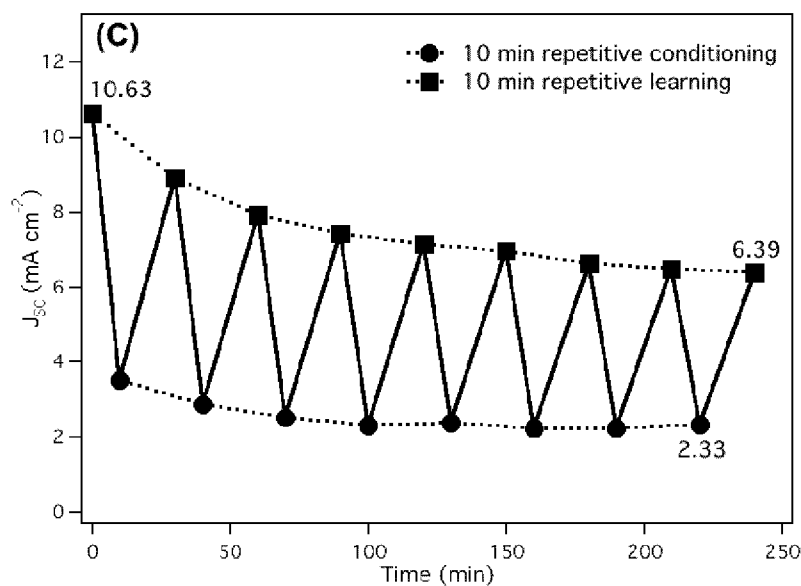


Figure 2 C

(57) **Abstract:** The present invention concerns photoelectronic and/or optoelectronic learning device and/or memory device. In an embodiment, the device is a dye-sensitized solar cell. The short circuit photocurrent density (J_{sc}) of the device, and wherein a degree of a J_{sc} drop, depends on how long the device is being illuminated. During a subsequent absence of illumination, J_{sc} of the device increases in a time dependent manner. Furthermore, said degree of J_{sc} drop depends on the number of cycles of successive illumination and absence of illumination. The device of the invention may be considered as a self-evolving hardware that translates learning into long lasting changes in electronic parameters, akin to the neuronal network in the human brain. The device of the invention mimics traits of intelligent learning through optical stimulus. Particularly, the device exhibits and memorizes variations in its electronic properties differently, depending on the duration and the repetition rate of previous light exposure.



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Optoelectronic and/or Electrochemical Learning Device

Technical Field

- 5 The present invention relates to an optoelectronic and/or electrochemical learning and/or memory device.

Background Art and Problems Solved by the Invention

- 10 There has been a long lasting desire for building machines capable of human intelligence, involving reasoning, decision making, or understanding. The most important prerequisite underlying these abilities is learning by experience. To achieve this goal, current technology is mostly based on sophisticated software engineering, may it be smart algorithms for internet search engines or image recognition. However, for artificial intelligence to fully thrive,
- 15 powerful software ought to be complemented by self-evolving hardware that translates learning into long lasting changes in electronic parameters, akin to the neuronal network in the human brain.

- Learning through vision, may it be reading a text or observing the environment, is one of the
- 20 most important traits for intelligent beings. In the quest for implementing this ability into machines like self-navigating vehicles, a complicated interplay between optical sensors and the corresponding image recognition software is utilized, requiring immense computing power and hence energy consumption. A major step towards solving this problem would be a self-evolving electronic component in response to visual stimuli. Such self-adapted but non
- 25 optical learning hardware has been realized before¹⁻⁴. In terms of combining both optical sensing and energy saving characteristics, the most fitting candidate would be a solar cell. It is first and foremost imperative to define the meaning of visual learning. Very generally, learning involves two major steps, intake and memory of the information to be learned. Notice that smart learning is not just simply memorizing all incoming data or a skill but rather
- 30 entails the ability to distinguish between which kind of information is important enough to store in the long term memory and which can be safely discarded after its short term use. In this way, storage capacity can be maximized and constantly updated with only the most relevant data, as is performed by the human brain. Such decision making requires triggers that determine which information should be kept. For humans, stimuli are numerous, they can

span from subconscious to conscious ones. Learning from mistakes for instance is a prominent subconscious trigger, whereas learning by repetitively practicing is a conscious one. It is far beyond our capabilities to simulate the full complexity of the human brain in this matter. Therefore, as a proof of concept, we solely focus on two main pillars of intelligent
5 perceptive learning, namely exposure time and repetition rate dependent learning, employing a simple light source as the visual trigger.

It is an objective of the present invention to provide a device the electronic properties of which are dependent on an optical input.

10

It is an objective of the invention, to provide a device that memorizes or learns on the basis of optical input.

It is an objective of the invention to provide a device that is capable of distinguishing from
15 different types of optical inputs, for example optical inputs of different duration, thereby distinguishing between "important" and "not important" and/or between "more important" and "less important".

It is an objective to provide a device that is capable of gradually distinguishing optical inputs
20 and/or memorizing gradually from optical inputs.

It is an objective of the invention to provide a device that is capable of learning or memorizing from repeated optical stimuli, wherein the device exhibits more learning the more the optical stimulus is repeated.

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It is an objective of the invention to provide a device that has an inherent electronic property, wherein the electronic property is decreased and/or increased as a consequence of an optical stimulus, the duration of an optical stimulus and/or the repetition of the optical stimulus.

30 It is an objective of the invention to provide a device that has an electronic measurement entity, wherein the measurement entity is decreased and/or increased as a consequence of an optical stimulus, the duration and intensity of an optical stimulus and/or the repetition of the optical stimulus.

It is an objective of the invention to provide a device that has an output current, wherein the output current is decreased and/or increased as a consequence of an optical stimulus, the duration of an optical stimulus and/or the repetition of the optical stimulus.

- 5 It is an objective of the invention to provide a device that gradually returns to starting or neutral status in the absence of an optical learning input. It is an objective to provide a device that is capable of "forgetting", in particular forgetting in the case of prolonged absence of a stimulus.
- 10 It is an objective to address the technical challenges above without programming and configuration other than adjusting structural, chemical and/or hardware components. It is an objective to provide a hardware entity that addresses the problems above.

- It is an objective of the invention to provide a device that changes its chemical properties in response to the past optical stimuli as described above. This behaviour mimics synaptic plasticity occurring through learning in human brain. This characteristic allows the simulation and fabrication of artificial neuronal networks.
- 15

The present invention addresses the problems depicted above.

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Further aspects and preferred embodiments of the invention are defined herein below and in the appended claims. Further features and advantages of the invention will become apparent to the skilled person from the description of the preferred embodiments given below.

25 **Summary of the Invention**

- Remarkably, the inventors provide an optoelectronic and/or electrochemical device that exhibits traits of intelligence, and in particular of learning and/or memorizing. The device's capability of learning is based on an optical stimulus, such as exposure to light, which affects the electronic properties of the device.
- 30

Remarkably, the device of the invention provides an optoelectronic sensor mimicking traits of visual learning and/or an optoelectronic sensor exhibiting visual learning.

In an aspect, the present invention provides an optoelectronic, photoelectronic and/or electrochemical learning device.

5 In an aspect, the present invention provides an optoelectronic, photoelectronic and/or electrochemical memory device.

In an aspect, the present invention provides a device, the electronic properties of which are dependent on a light stimulus, duration of the light stimulus and/or repetition of the light stimulus and/or intensity of the light stimulus.

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In an aspect, the present invention provides a device exhibiting a conditioning phase and a memorizing phase.

In an aspect, the present invention provides a self-adapted, optical learning hardware.

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In an aspect, the present invention provides a device which has a property, wherein a value of said property changes as a function of duration of a conditioning phase and/or as a function of light intensity during the conditioning phase, in which conditioning phase the device is exposed to an optical stimulus.

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In an aspect, the present invention provides a device which has a property wherein a value of said property changes as a function of the number of cycles of successive conditioning and absence of conditioning. Preferably, the more cycles the device experiences, the more the property changes.

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In an aspect, the present invention provides a photoelectronic and/or optoelectronic learning device and/or memory device, which has an electronic property, wherein a value of said electronic property changes as a function of duration of a conditioning phase and/or as a function of light intensity during said conditioning phase, in which conditioning phase the device is exposed to an optical stimulus, and wherein said device is susceptible of exhibiting an information loss phase subsequent to said conditioning phase, said information loss phase being characterized by the absence of conditioning and/or light stimulus, wherein, during said information loss phase, said value of said property changes with opposite sign compared to

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said conditioning phase, such that the value of said electronic property changes in direction of a starting point value as a function of time during said information loss phase.

5 In an aspect, the present invention provides the use of a dye-sensitized solar cell as a memory and/or learning device.

In an aspect, the invention provides novel photoelectric conversion devices, in particular novel dye-sensitized solar cells.

10 In an aspect, the present invention provides a photoswitch comprising the device of the invention.

In an aspect, the present invention provides a sensor comprising the device of the invention.

15 In an aspect the present invention provides the device of the invention in robotics, in particular sensor or artificial eyes for robotics, self-navigating vehicles, self-evolving optoelectronic/electrochemical circuits and networks, and surveillance systems.

Brief Description of the Drawings

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Figure 1 shows (A) J_{SC} evolution as measured at 100 mW cm^{-2} (1 sun) after a 60 min 1 sun illumination period at open circuit, representing the optical, time dependent information weighting or conditioning ability of the DSC. Inset depicts the chemical structure of the Co(II/III)(terpy)₂ complex. (B) J_{SC} recovery time when leaving the 60 min conditioned DSC in the dark. (C) J_{SC} evolution under continuous 1 sun illumination for a period of 5 min, (D) 10 min, and (E) 20 min, followed by resting the cell in the dark, representing selective learning or information loss. (F) $\Delta J_{SC} = J_{\text{initial}} - J_{\text{dark}}$ as a metric for smart selective learning (or information loss) after various conditioning times.

30 **Figure 2** shows (A) J_{SC} evolution of the DSC undergoing multiple learning cycles each consisting of 5 min (C) 10 min, and (E) 20 min illumination followed by 20 min resting in the dark. The dotted line with the squares depicts the learning curve of the solar cell. An exponential fit to this repetitive learning curve may be drawn along the dotted line linking the

squares. (B) J_{SC} recovery time after the solar cell's repetitive learning at 5 min, (D) 10 min, and (F) 20 min of illumination time as compared to the corresponding one time learning.

Figure 3 illustrates an image recognition system based on an array of photovoltaic cell in accordance with an embodiment of the invention.

Figure 4 illustrates an artificial optical neural network comprising a plurality learning photovoltaic cells according to an embodiment of the invention.

Hereinafter, preferred embodiments of the device of the invention are described, in order to illustrate the invention, without any intention to limit the scope of the present invention.

Detailed Description of the Preferred Embodiments

The present invention relates to photoelectronic, optoelectronic and/or electrochemical learning and/or memorizing devices.

The device of the invention preferably exhibits properties that are reminiscent of human learning and/or memorizing.

In an embodiment, the device of the invention is preferably susceptible of exhibiting a first phase or conditioning phase, where an external stimulus affects at least one property of the device, and a second phase, where conditioning is absent. The second phase may also be referred to as "forgetting phase", "information loss phase", or "fading out phase". In the second phase, a property of the device acquired during the conditioning phase is preferably gradually lost in a time dependent manner.

The conditioning phase is preferably characterized by the presence of a stimulus acting on the device and capable of affecting at least one property of the device. Said stimulus is preferably capable of inducing the learning process in accordance with the invention. On the other hand, the "information loss phase" is characterized by the absence of a stimulus that is suitable to affect said at least one property of the device.

Said stimulus is preferably an optical stimulus, preferably in the form of light. Depending on

the device, the device may be constructed to require one or more particular wavelengths or wavelength ranges of light in order to exhibit the learning characteristics, light of a particular intensity, irradiation and combinations of the aforementioned. In the examples, the light stimulus that was used for testing an exemplary device of the invention is light irradiation of
5 100mWcm⁻² (1 sun equivalent) produced by a xenon lamp.

Preferably, in the device of the present invention, the learning process expresses itself in the form of an impact on the properties of the device. Accordingly, by way of an optical and/or light stimulus, at least one property of the device is affected.

10

In an embodiment, said "property" is a physical property, for example a physically property that is measurable as a physical entity, preferably quantitatively measurable in terms of a physical entity or physical unit.

15 Preferably, said "property" is an electronical property of the device. Preferably, said property is a measurable electronic property of the device, preferably an electronic measurement entity.

In a particular, preferred embodiment, the "property" is selected from the output current density and the short circuit current density (J_{SC}) of the device.

20

In an embodiment, the device of the invention is an electrochemical device.

In an embodiment, the device of the invention comprises an electrolyte.

25 In an embodiment, the device of the invention is a photoelectric conversion device.

In an embodiment, the device of the invention is a solar cell.

In an embodiment, the device of the invention is a dye-sensitized solar cell (DSSC).

30

In an embodiment, the device of the invention comprises a redox-couple. Preferably, the device comprises an electrolyte comprising said redox-couple.

For the purpose of the present specification, the term "comprising", and its various grammatical forms, is intended to mean "includes, amongst other". It is not intended to mean "consists only of".

- 5 In an embodiment, the device of the invention comprises a redox-couple selected from cobalt complexes. In the art, numerous cobalt complexes are disclosed for use as redox-mediators. Such redox couples are disclosed, for example, in international application WO2012/114315.

10 The redox couple is preferably provided by cobalt complexes, preferably a pair of cobalt complexes comprising cobalt atoms in oxidation states II^+ and III^+ . The device preferably comprises a first cobalt complex, in which the cobalt atom is in the II^+ oxidation state and a second cobalt complex, in which the cobalt atom is in the III^+ oxidation state. The ligands of the cobalt atom in said complexes may be selected as appropriate by the skilled person, for example from ligands disclosed in WO2012/114315 or ligands known from other prior art
15 documents. The two cobalt complexes may be identical in terms of non-charged ligands or different. The cobalt complexes are preferably added to the electrolyte of the device during device fabrication. When illuminated, the concentrations of the Co^{II^+} and Co^{III^+} may change, due to electron transfer occurring (Co^{II^+} being rapidly oxidized at the photoanode), but after illumination the amounts of the Co^{II^+} and Co^{III^+} should return to initial concentrations of the
20 complexes as added.

Interestingly, if the device is a dye-sensitized solar cells, the characteristics in terms of the present invention are improved if the concentrations of said cobalt complexes are different compared to concentrations used for solar cells in which power conversion efficiency is
25 maximized.

In an embodiment, the Co^{II^+} complex is present at a concentration smaller than the concentration of said Co^{III^+} complex.

- 30 In an embodiment, the Co^{II^+} complex is present at a concentration smaller than or equal to $\frac{3}{4}$ of the concentration of said Co^{III^+} complex.

In an embodiment, the Co^{II^+} complex is present at a concentration smaller than or equal to $\frac{1}{2}$

of the concentration of said $\text{Co}^{\text{III}+}$ complex.

In an embodiment, the $\text{Co}^{\text{II}+}$ complex is present at a concentration smaller than or equal to 1/3 (one third) of the concentration of said $\text{Co}^{\text{III}+}$ complex.

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In an embodiment, the $\text{Co}^{\text{II}+}$ complex is present at a concentration of ≤ 0.25 M, preferably ≤ 0.22 M, more preferably ≤ 0.20 M, even more preferably ≤ 0.15 M, and most preferably ≤ 0.10 M in an electrolyte of said dye-sensitized solar cell.

- 10 In an embodiment, the $\text{Co}^{\text{III}+}$ complex present at a concentration of ≥ 0.08 M, preferably ≥ 0.10 M, more preferably ≥ 1.13 M, even more preferably ≥ 0.15 M, and most preferably ≥ 0.18 M in an electrolyte of said dye-sensitized solar cell.

- 15 In an embodiment, the $\text{Co}^{\text{II}+}$ complex is present at a concentration of ≤ 0.22 M and the $\text{Co}^{\text{III}+}$ complex is added at a concentration of ≥ 0.08 M. Preferably, the $\text{Co}^{\text{II}+}$ complex is present at a concentration of ≤ 0.20 M and the $\text{Co}^{\text{III}+}$ complex is present at a concentration of ≥ 0.1 M. Even more preferably, the $\text{Co}^{\text{II}+}$ complex is present at a concentration of ≤ 0.18 M and the $\text{Co}^{\text{III}+}$ complex is added at a concentration of ≥ 1.13 M.

- 20 The above concentrations preferably apply to the concentration of the complexes present in the electrolyte when the device is fabricated (before the first use) and/or after keeping the device in the dark, for example, for 1 day.

- 25 In a preferred embodiment, a property of the device is affected, for example altered, in the presence of the optical stimulus. As mentioned above, the property is preferably a quantitatively measurable physical unit or entity.

- 30 Preferably, the value or amount of the physical entity measured on the device is either increased or reduced as a result of the stimulus. While in the examples shown, an optical stimulus results in a reduction of the device's short circuit current (J_{SC}), the present invention is not limited to this particular example.

In a preferred embodiment, the property of the device changes as a function of time of the

conditioning and/or absence of conditioning, that is, of the duration of the conditioning phase and/or of the duration of absence of conditioning.

For the purpose of the present specification, the expressions "starting point" and "end point" are used. The "starting point" refers to the moment where the device starts to be exposed to a stimulus. The "starting point" may therefore be at the end of said second phase, where no conditioning took place. The "first starting point" is preferably the very first time the device is exposed to a light stimulus, or to the moment after which all or most of the previously changes with respect to the property have returned to the base value.

The property of the device at the starting point is the "starting point value" of the measurable physical entity.

The expression "end point" refers to the moment where a conditioning phase ends and an "information loss phase" starts.

In Figures 2A, 2C and 2E, showing an exemplary device exposed to repetitive cycles of learning/conditioning, the filled squares represent successive starting points and the filled circles represent successive end points.

In an embodiment, the device exhibits a property at a starting point, which is defined a value of said physical entity at said starting point (the "starting point value"). The starting point value represents the property of the device before the optical stimulus or at the start of the presence of the optical stimulus. "The first starting point value" may also be referred to as "base value" or "zero value", which reflects that the property at its original value that it had before any conditioning phase took place.

During conditioning, preferably in presence of continued exposure to the optical stimulus, the amount or value of the physical entity will be reduced or increased compared to said starting point value as a consequence of the optical stimulus during conditioning.

The moment at the end of conditioning, where said conditioning stops and said "information loss phase" starts is referred to as an "end point" in this specification. The amount or value of the property at this moment is referred to as "the end point value".

One may say that, at the end of a conditioning phase, the device receives no more information to be memorized.

- 5 Preferably, the amount of the property is altered in dependence of the duration of the optical stimulus. Preferably, the amount of the property is gradually or regularly altered as the duration (time) of the optical stimulus increases.

10 Preferably, the change of the amount of the property in the presence of the optical stimulus is a function of time.

At the end of the conditioning phase or optical stimulus, the property of the device has preferably reached said "end point value". The end point value is different from the start point value, for example higher or lower, and the difference between the starting and the end point
15 is the consequence of the optical stimulus, preferably the consequence of the duration of the optical stimulus, which preferably corresponds to the duration of said conditioning phase.

In an embodiment of the device of the invention, said value of said property changes from a starting point value at the beginning of said conditioning phase to an end point value at the
20 end of said conditioning phase, wherein said change is a function of time, and wherein the end point value is different from said starting point value.

In a preferred embodiment, the rate of the change of the amount of the property during conditioning is reduced with increased time of conditioning and at some point the property
25 does not change any more. In other words, the device preferably exhibits saturation of conditioning, where further conditioning does not result in any further change of the property. Preferably, during continued conditioning, the value of the property asymptotically approaches a limit value which is generally not trespassed during normal functioning and normal operation of the device. Saturation is preferably achieved as said property approaches
30 said limit value. In a graph such as those shown in Figs 1A, 1C and 1E, depicting the value of the electronic property as a function of time, the rate of the change corresponds to the tangent of the function line, wherein saturation reflects the inclination of the tangent approaching 0 (zero) and/or the graph line approaching horizontal.

In a preferred embodiment, the property is output currents and/or short circuit current/photocurrent density (J_{SC}), and the amount of said current, at the end point, is lower compared to amount of the current at said starting point. In accordance with this embodiment, the exposure to an optical stimulus (conditioning) affects J_{SC} by causing a decrease of J_{SC} , which decrease is time dependent, at least for some time after the "starting point". Of course, saturation may occur, wherein J_{SC} is no longer decreased even in presence of continued conditioning.

In a preferred embodiment, a value of said property is an inherent property of the device at a given moment in time.

In some preferred embodiments, the device of the invention is a solar cell, which may imply that the optical stimulus must be present for determining the property (e.g. value of J_{SC}). In other words, in some embodiments, the property of the device cannot be determined in the absence of the optical stimulus. The property is preferably inherently present in the device, even in the absence of the optical stimulus. In this particular embodiment, the property of the device can be determined at any time during the absence of the optical stimulus by applying the optical stimulus.

The present device preferably distinguishes from devices in which a (optical) stimulus results in a particular electronic property, such as a particular voltage or current. In the present device, the optical stimulus results in an inherent change of the property of the device, which change is in some way "stored" in the device, in the absence of any software and storage medium. The property is not the direct result of a particular stimulus such that, once a particular stimulus is exerted, always the same property is obtained. In contrast, in the device of the invention, the property preferably changes as a function of time of exposure to a constant, unchanging stimulus.

In an embodiment, the device of the invention is a hardware based device and/or which can operate in the absence of any program code, software and computer storage medium, such as RAM, ROM, and so forth.

In an embodiment of the device of the invention, said value of said property is the

consequence and/or affected by previous conditioning and/or absence of conditioning.

In prior art devices, a given (optical) stimulus generally always results in the same property exhibited by the device, whereas, in the present invention, the value of the property is
5 dependent on the stimulus or stimuli experienced previously by the device, such as the duration of a previous conditioning and/or absence of conditioning.

In an embodiment, the property of the device after conditioning, at an "end point" is contained, for example stored, memorized and/or inherently present in the device, preferably
10 at least for a certain period of time. Preferably, the property is further lost gradually as a function of time of absence of the stimulus.

Accordingly, if the amount of the property is determined just at or shortly after the end of the conditioning phase, the amount of the property preferably corresponds to said end point value
15 and/or is at least closer to said end point value than to said starting point value. "Shortly after" may here refer to a time interval that is short compared to the duration of the conditioning phase, for example representing up to 5% of the duration of the conditioning phase.

Remarkably, in the absence of said optical stimulus ("information loss phase"), the amount of
20 said property changes again, in particular it changes back towards the starting point value in the prolonged absence of the optical stimulus.

The device of the present invention preferably exhibits time dependent "forgetting" or, in positive wording, said "information loss" is time dependent and/or dependent on the absence
25 of the optical stimulus.

In an embodiment, the device of the invention is susceptible of exhibiting an information loss phase subsequent to said conditioning phase, said information loss phase being characterized by the absence of conditioning and/or light stimulus, wherein, during said information loss
30 phase, said value of said property changes with opposite sign compared to said conditioning phase. Preferably the value of said property changes in direction towards said starting point value as a function of time.

In an embodiment, in the absence of an optical stimulus, the amount or value of the property

changes preferably in the direction of the starting point value. In other words, during the information loss phase, the value of the property changes in a manner opposite (with inversed sign) to the change that takes place during the conditioning phase. The rate of the change of the property during the information loss phase may be the same or different from the rate of the change during the conditioning phase.

Accordingly, after a conditioning phase and during an information loss phase, the amount of said property will change towards said starting point value, for example will get closer to the starting point value.

Preferably, the return to the starting point value is time dependent. Preferably, the longer the absence of an optical stimulus, the closer the value or amount of the property will get to the starting point value. Preferably, in an absence of an optical stimulus (but after an optical stimulus had taken place), the amount of the physical entity returns gradually and/or regularly returns towards said starting point value.

Preferably, the change of the amount of the property in the absence of the optical stimulus (but after an optical stimulus had occurred previously) is a function of time.

Preferably, in the absence of the optical stimulus, the amount of the property changes from an end point value as a function of time, preferably with inversed sign compared to the change that takes place during an optical stimulus.

Accordingly, if the conditioning results in a decrease of the amount or value of the property, the absence of conditioning will result in an increase of the amount or value of the property, or vice versa.

In an embodiment, the conditioning results in an increase of the value or amount of the electronic property of the device, for example an increase of output current. In this case, the subsequent absence of conditioning, after conditioning had taken place, will have the consequence that the output current decreases, preferably towards the value it had before conditioning.

In another, preferred embodiment, the conditioning results in a decrease of the value or

amount of the electronic property, for example an increase of the device's short circuit photocurrent density (J_{SC}). In this case, the subsequent absence of conditioning, after conditioning had taken place, will have the consequence that the output current increases, preferably towards the value it had before conditioning. It being understood that in the
5 exemplary case of a dye-sensitized solar cell a light stimulus is required for determining the actual property, that is, said J_{SC} .

One may say that the device preferably exhibits time-dependent forgetting. The time dependent forgetting reflects the situation where the stimulus was not important, since not
10 recurring, and is thus forgotten by the device, which will eventually exhibit a property that corresponds to the property at the starting point, at the beginning of the optical stimulus, or inherently present in the device before said optical stimulus.

In a preferred embodiment, the property is output currents and/or short circuit current density
15 (J_{SC}), and the amount of said current, in a device exposed to an optical stimulus and subsequently to a period where said optical stimulus is absent, is higher than the amount of said current after the optical stimulus and/or before said period where the optical stimulus is absent.

20 In some embodiments, the absence of an optical stimulus results in a change of the value of the property in the sense towards the starting point value, but the value will never reach said starting point value, even after prolonged absence of said optical stimulus.

25 In an embodiment of the invention, during the absence of conditioning, the value of the property preferably asymptotically approaches the starting point value with time.

In accordance with this embodiment, the conditioning prior to the "information loss phase" may be a partially irreversible event and/or may be an engraving event, which will always leave a trace in the device. After such an engraving event, the device will no longer be able to
30 reach said starting point value.

In some embodiment, the very first conditioning phase may be conducted to be such an engraving event, such that it is always possible to say whether the device has already been

exposed to an optical stimulus previously. In some embodiments, the engraving event is time dependent and requires that the optical stimulus has taken place for a particular period of time, and/or the engraving event may depend on particular conditions (light conditions, such as light intensity) to take place.

5

In accordance with the above, the device may be exposed to engraving conditioning such that there will be no complete return to the starting point value even in prolonged absence of conditioning. In such a case, the absence of the optical stimulus may result in the amount of said property approaching a limit value. The limit value may be lower or higher than the starting point value, depending on the effect of the conditioning on the amount of the physical entity. For example, in case the conditioning results in a reduction of current output or J_{SC} , the occurrence of an engraving event has the consequence that the amount of said current will never be as high as it has been before the engraving event.

15 In some embodiments, the first exposure to an optical stimulus may constitute an engraving event.

In a preferred embodiment, the device of the invention preferably exhibits learning as a result of repetition. In an embodiment, repeated exposure to an optical stimulus results in slower "forgetting" and/or increases memorizing, for example in the absence of the optical stimulus.

20 Preferably, repetition refers to cycles of successive exposure to conditioning phases and absence of conditioning ("information loss phase"), preferably successive exposures to an optical stimulus and absences of the optical stimulus. One cycle is preferably composed of a conditioning phase and one information loss phase. A second cycle starts with renewed conditioning after the first information loss phase.

25 The duration of the conditioning and, independently, of the information loss phase are preferably parameters that affect the properties of the device. In some embodiments, these parameters need to be adjusted such that the device exhibits the learning behavior reported herein.

In an embodiment, the device of the invention has a property, wherein a value of said property is susceptible of changing as a consequence or function of repeated cycles of conditioning and

absence of conditioning.

During repeated conditioning, preferably as a consequence of exposure to cycles as described above, the amount of the property will be reduced or increased compared to said starting point value as a consequence of the repeated conditioning. Preferably, the amount of the property is altered in dependence of the number of cycles. Preferably, the amount of the property is gradually or regularly altered as the number of successive cycles increases.

Preferably, the change of the amount of the physical entity in the presence of repeated exposure to the optical stimulus is a function of the number of cycles of exposure and of the time periods of said cycles.

In an embodiment, the exposure of the device to repeated and/or successive cycles of conditioning/absence of conditioning results in a slower return towards said starting point value, compared to the return in the absence of repetition.

Preferably, in a device exposed, for example to two cycles of conditioning and absence of conditioning, the property of the device is different than the property of a device that was exposed to only one cycle of conditioning and absence of conditioning.

For the purpose of describing the invention, the following definitions are made: Before any exposure to an optical stimulus, the device exhibits the first starting point value. In other words, the property of the device in that moment is expressed by the first starting point value. After a first conditioning, the device exhibits a first end point value. After the first conditioning, the device is exposed to a first information loss phase. At the end of the first information loss phase, the device exhibits the second start point value. After the second conditioning, the device exhibits a second end point value, and after a second information loss phase, it exhibits the third starting point value. At the beginning of the third cycle, the device thus exhibits the third start point value. Renewed conditioning results in a third end point value, and subsequent information loss to a fourth start point value. The numbering of the phases and values may be applied to any number of cycles.

In accordance with the above, when referring to repetitive conditioning, one may refer any number of cycles, where any cycle starts with an N^{th} starting point value, proceeds to an N^{th}

end point value at the end of the N^{th} conditioning phase, and, after the N^{th} information loss phase, the next cycle starts with the property exhibiting an $(N+1)^{\text{th}}$ starting point value.

5 In accordance with the invention, the parameters of the cycles (e.g. duration, light condition) may be chosen such that the repeated exposure results in improved memorizing.

10 In an embodiment of the device of the invention, an N^{th} starting point value of said electronic property at the beginning of an N^{th} conditioning phase is different from an $(N+1)^{\text{th}}$ starting point value of said electronic property at the end of an N^{th} information loss phase, the information loss phase being characterized by the absence of conditioning.

15 In an embodiment of the device of the invention, an N^{th} starting point value of said property at the beginning of an N^{th} conditioning phase is different from an $(N+1)^{\text{th}}$ starting point value of said electronic property at the beginning of an $(N+1)^{\text{th}}$ conditioning phase.

20 In an embodiment of the device of the invention, an N^{th} end point value of said property at the end of an N^{th} conditioning phase is different from an $(N+1)^{\text{th}}$ end point value of said property at the end of an $(N+1)^{\text{th}}$ conditioning phase (or at the beginning of the $(N+1)^{\text{th}}$ information loss phase).

25 Of course, the difference in the expression "is different from" above depends on whether the conditioning results in increasing or decreasing the value of the property. Accordingly, this expression refers to either "increased with respect to" (or "higher than") or "decreased with respect to" (or "lower than").

30 In a particular embodiment, the device is such that the value or amount of the property is increased as a consequence of conditioning. In accordance with this embodiment, the second starting point value is higher than the first starting point value. More generally, the $(N+1)^{\text{th}}$ starting point value is higher than the N^{th} starting point value. This is a consequence of repetition in accordance with the invention, wherein the parameters of the cycles (duration of conditioning and absence of conditioning) are chosen accordingly. Preferably, the $(N+1)^{\text{th}}$ end point value is higher than the N^{th} end point value.

In another, more preferred particular embodiment, the device is such that the value or amount of the property is decreased as a consequence of conditioning. In accordance with this embodiment, the second starting point value is lower than the first starting point value. More generally, the $(N+1)^{\text{th}}$ starting point value is lower than the N^{th} starting point value. This is a consequence of repetition in accordance with the invention, wherein the parameters of the cycles (duration of conditioning and absence of conditioning) are chosen accordingly. Preferably, the $(N+1)^{\text{th}}$ end point value is lower than the N^{th} end point value.

In a preferred embodiment, where the property is the device's short circuit current density (J_{SC}), the J_{SC} at the N^{th} starting point is lower than at the $(N+1)^{\text{th}}$ starting point. Preferably, the J_{SC} at the N^{th} end point is lower than at the $(N+1)^{\text{th}}$ end point. This refers to the values of J_{SC} directly at the end of conditioning.

In other words, the return back in direction towards the starting point value may be diminished with each cycle that is added, with each additional "return" resulting in a starting point value that is increasingly further away from the first starting point value.

As a consequence, the repeated exposure to conditioning results in improved learning in that the properties of the device are increasingly and/or more persistently changed, for example in the sense of the conditioning, for example, in the direction of an end point.

The scheme described is preferably exhibited until a saturation is observed, where exposure to additional cycles (e.g. to the N^{th} cycle) does not result to any further substantial change of the $(N+1)^{\text{th}}$ starting point value and/or end point value. At saturation, the $(N+1)^{\text{th}}$ starting point value is substantially equal to the N^{th} starting point value, and/or the $(N+1)^{\text{th}}$ end point value is substantially equal to the N^{th} end point value.

In some embodiments of the invention saturation may take place after 2-50 cycles, preferably 3-20 cycles, preferably 4-15 cycles, most preferably 5-10 cycles.

In an embodiment, saturation also occurs as a result of continued conditioning, for example in the absence of cycles, where the property does not change any more.

The parameters of the cycles (duration of conditioning, parameters of illumination, duration of information loss) may preferably be adjusted so as to control when saturation takes place, that is, after how many cycles or after how much time. Furthermore, the saturation may be interrupted by a prolonged conditioning phase and/or prolonged learning phase resulting in a further change of an end point value.

In accordance with an embodiment, the following embodiments are provided with respect to the duration of the conditioning phase and the information loss phase.

- 10 In a preferred embodiment, the conditioning phase lasts from 1-60 minutes, preferably 2-40 minutes, more preferably 4-30 minutes, even more preferably 5-30 minutes. In a preferred example, the duration of the conditioning phase is from 10-60 minutes.

- 15 Since the light intensity experienced by the device during the conditioning phase preferably also affects the value of the electronic property, the exemplary durations of the conditioning phase also depend to some extent on the intensity during the conditioning phase. Preferably, the above durations apply to a light intensity corresponding to a "one sun equivalent", preferably 100 mWcm^{-2} .

- 20 Preferably, the information loss phase (absence of conditioning) lasts from 3 minutes to 12 hours, preferably 5 minutes to 8 hours, more preferably 10 minutes to 6 hours, and most preferably 15 minutes to 3 hours.

- 25 In an embodiment, the above time periods (absence of conditioning) correspond to the duration required to compensate 50% of the change of the property experienced during conditioning. As an example for illustrating this feature, if the property is J_{SC} , which is decreased by 8 mAcm^{-2} during a given conditioning phase, the device preferably requires absence of conditioning for 3 minutes to 12 hours in order to get 4 mAcm^{-2} (50% of the loss) closer to the starting point value. The preferred time periods given above also apply.

30

Generally, the time of absence of conditioning required for "forgetting" a particular amount of the change of property will also be depending on the duration and characteristics of the preceding conditioning phase.

In an embodiment, the device is a dye sensitized solar cell that acts as a photoswitch determined by a high and low photocurrent, representing the on and off state.

- 5 In an embodiment of the device, said property is the short circuit current density (J_{SC}) of the device, and a degree of a J_{SC} drop depends on how long the device is being illuminated. Preferably, the longer the device is exposed to light, the more the photo current decreases.

10 In the device of the invention, switching may depend on how long the device is being illuminated.

Preferably, the device memorizes said property, such as the photocurrent changes in a time dependent manner.

- 15 In an embodiment of the device, this illumination time dependent photo current degradation reflects human learning through vision, where the degree of photo current change mirrors the degree of learning. I.e., this behavior is similar to how the human brain works: It learns more efficiently the longer the optical input lasts.

- 20 In an embodiment, the device also memorizes the photo current changes.

In an embodiment, the device memorizes the drop in current for a longer time the more frequently it undergoes cycles of illumination (conditioning phase) and in the dark (forgetting phase). Preferably, said degree of J_{SC} drop depends on the number of cycles of successive
25 illumination and absence of illumination.

In some embodiments, the phenomenon reported in this specification mirror repetitive learning in the human brain.

- 30 In an embodiment of the invention, the device can memorize durations of light exposure and/or repetition of light exposure.

More generally, the device of the invention preferably provides an optoelectronic sensor mimicking traits of visual learning and/or an optoelectronic sensor exhibiting visual learning.

The device of the invention may be considered as a self-evolving hardware that translates learning into long lasting changes in electronic parameters, akin to the neuronal network in the human brain. In the particular examples herein below, we introduce a solar cell that mimics traits of intelligent learning through optical stimulus. Particularly, the device exhibits and memorizes variations in its electronic properties differently, depending on the duration and the repetition rate of light exposure. These traits are reminiscent to learning by experience, allowing our solar cell to act as a self-sufficient and smart electronic element for perceptive artificial intelligence.

The device of the invention may be used in various domains. For example, the device may be used in robotics, in particular as sensor or artificial intelligent eye for robotics. The device may be used as sensor or artificial eye for a self-navigating vehicle, for example. Furthermore, the device may be used as sensor or artificial intelligent eye in surveillance systems. In an embodiment, the device of the invention is used in or part of self-evolving optoelectronic/electrochemical circuits and networks.

The device may also be used as a photoswitch for one or more selected from the group consisting of robotics, vehicles, surveillance systems and self-evolving optoelectronic/electrochemical circuits and networks.

Examples

Example 1: Dye-sensitized solar cells functioning as learning devices

1. Fabrication of dye-sensitized solar cells having learning capability

The opto-electronic learning sensor is comprised of a dye sensitized solar cell (DSC) fabricated according to the following steps: Fluorine doped tin oxide (FTO) glass (Nippon Sheet Glass NSG10) was cleaned by heating on a hotplate at 500°C for 30 minutes. Then, this glass was immersed twice in a 40 mM TiCl_4 solution in water for 30 minutes at 70°C to deposit the TiO_2 blocking layer on FTO. On this glass substrate, a 2.5 μm mesoporous transparent TiO_2 film was screen printed using Dyesol 30 NRT TiO_2 paste. After sintering this layer at 500°C for 30 min, it was sensitized with the organic dye Y123 by immersion into

a 0.1 mM Y123 and tertbutanol-acetonitrile (1 to 1 volume to volume) solution for 12 hours. This photoanode was sealed together with a platinum coated FTO glass acting as the counter electrode utilizing a 25 μm thick Surlyn film. The electrolyte being injected into this sealed solar cell consists of the redox shuttle cobalt(II)(bis-terpyridine) as a
5 bis(trifluoromethane)sulfonamide (TFSI) salt at the concentration of 0.05 M and Co(III)(terpy)₂TFSI at the concentration of 0.2 M together with 0.1M LiTFSI and 0.1M tertbutylpyridine (TBP) in acetonitrile (ACN). Note that for this solar cell to exhibit learning and memorizing effects, the cobalt(II)(bis-terpyridine) concentration as to be lower than cobalt(III)(bis-terpyridine), contrary to the standard high efficiency solar cells in which more
10 of the reducing species cobalt(II)(bis-terpyridine) should be present.

These solar cells distinguish from previously disclosed cells in that the concentration of the redox couple is below the concentration that is typically used with the goal of optimizing solar cell efficiency.

15 The typical Co(II/III) concentrations for a non learning dye sensitized solar cell are 0.2 M for Co(II) and 0.06 M for Co(III), the opposite to what is being employed in this learning cell.

2. Measurement Methods

20 To investigate the solar cell's learning effect, a photocurrent – potential curve was recorded by a Keithley sourcemeter, while the cell was illuminated at 100 mWcm^{-2} (equivalent to 1 sun) delivered by a xenon lamp. The short circuit photocurrent density (J_{sc}) obtained from this scan poses the initial J_{sc} prior to learning. The visual conditioning of the sensor that
25 induces the learning effect is performed by continuous illumination at 100 mWcm^{-2} under open circuit condition at room temperature for various time periods. The corresponding changes in J_{sc} after this conditioning were recorded via the above mentioned photocurrent – potential sweep at 100 mWcm^{-2} light exposure and represents the electronic signature of the sensor's learning.

3. Results and Discussion

3.1 Learning based on the duration of light exposure

When the solar cell fabricated as described above (no. 2) is illuminated at 100 mWcm^{-2} (equivalent to 1 sun) under open circuit condition at room temperature, an initial short circuit photocurrent density J_{SC} of 10.81 mA cm^{-2} is delivered at 1 sun (Figure 1A). However, with prolonged exposure to the same intensity while keeping the device at open circuit, the J_{SC} decreases exponentially, with a rapid decay in the first 20 min, after which the J_{SC} slowly saturates at a value of 2.20 mA cm^{-2} , a major drop of about 80% from the initial J_{SC} , as depicted in Figure 1A. Remarkably, when leaving this 60 min light soaked DSC in the dark, the deteriorated J_{SC} slowly recovers as highlighted in Figure 1B. More specifically, in the first 10 min in the dark, the J_{SC} increases from 2.20 mA cm^{-2} back to 6.42 mA cm^{-2} , regaining 59% of its initial value. With prolonged time in the dark, the J_{SC} grows progressively in the next 160 min, following a linear growth rate of about $16 \mu\text{A cm}^{-2} \text{ min}^{-1}$, ultimately reaching a value of 9.07 mA cm^{-2} as reflected in Figure 1B. This gradual J_{SC} recovery in the dark can be interpreted as the solar cell's information loss or forgetting process. More specifically, once the 60 min optical stimulus is turned off, the observed progressive J_{SC} recovery close to the initial value mirrors forgetting. Normally, forgetting is perceived as a bad trait, therefore at first superficial sight rendering our solar cell not particularly useful. Ideally, the solar cell should not forget, meaning that the J_{SC} of 2.20 mA cm^{-2} achieved after 60 min illumination induced learning should also remain in the dark for a prolonged time. However, this is simply memorizing without showing any traces of intelligent learning, which is namely the ability to distinguish between important information worthy of long term memory. Therefore, the signs of forgetting exhibited by our DSC entail the potential for such smart learning. As elaborated previously, one most straightforward and simple trademark of intelligent learning is triggered by the duration of the exposure to the information to be learned. Hereby, it is assumed that the importance for learning this particular optical information is governed by how long one is exposed to this object of interest. In order to investigate the capability of our DSC to perform such smart learning, the illumination time besides the so far 60 min is varied and the corresponding memory behaviour is studied. Since the J_{SC} deteriorates most rapidly in the first 20 minutes of illumination (Figure 1A), it is of more interest to study the selective learning effect within this time period of optical stimulation. Akin to the typical human learning process, one anticipates a shorter memory time at augmented illumination period. To test this hypothesis, three DSCs were each illuminated at 100 mW cm^{-2} for time intervals of 5 min, 10 min, and 20 min and their J_{SC} recoveries in the dark were monitored as illustrated in Figures 1C, D, E respectively. The longer this light conditioning takes place, the further the J_{SC} drops, as vividly demonstrated by the moderate drop by 2.11 mA cm^{-2} after 5 min light

exposure, whereas the J_{SC} decreases by 6.96 mA cm^{-2} and 8.35 mA cm^{-2} for 10 min and 20 min illumination respectively. Considering the amount of J_{SC} drop to electronically represent the weight or importance of the optical information to be learned, the longer the light stimulus, the more the solar cell recognizes this optical information source to be relevant.

5 Then, the extended exposed device should also recover the J_{SC} slower, in this way reflecting selective learning by keeping the learned information longer in memory. To verify this trend, we first investigate a short illumination time of 5 min, representing minor information relevance. After 5 min light soaking, the J_{SC} increases in the dark, closely reaching its initial J_{SC} within 10 min (Figure 1C). On the other hand, a more retarded J_{SC} recovery period of
10 about 50 min is present for the cell illuminated for 10 min (Figure 1D), if the recovery time is defined to be reaching within 90% of the original J_{SC} . An even further extension of the J_{SC} recovery time beyond 150 min is achieved after a longer light exposure of 20 min (Figure 1E), thus underlining the illumination time dependent learning behaviour of our DSC. In this context, it is helpful to establish the difference ΔJ_{SC} between the initial J_{SC} and the J_{SC} after
15 light exposure as an electronic metric for smart selective learning. Ideally, with prolonged resting time in the dark, ΔJ_{SC} should be as close to the value as right after the end of the illumination to show the cell's ability for memory retention. Figure 1F summarizes this ΔJ_{SC} for various illumination periods, revealing that the longer the light stimulation, the larger the ΔJ_{SC} in the dark at a given time, until the J_{SC} recovery time is reached, in which case the DSC
20 has completely forgotten the learned information. This trend expresses the DSC's ability to intelligently distinguish between important information marked by a long illumination period and to learn this information by memorizing it for an extended period of time. The device being optically conditioned for 60 min exhibits the longest memory, with J_{SC} recovery time reaching several days (information not shown here).

25 *3.2 Learning based on repetitive light exposure*

In the discussion under no. 3.1 above, our DSC exhibits intelligent selective learning based on the duration of light exposure. The most common method of learning is rather of the repetitive
30 manner, best illustrated by human learning. For instance, skills are optimally acquired by repeated practicing, since the brain typically tends to forget the just acquired information if not constantly recalled and refreshed. Conclusively, the desired learning capability of our DSC would be of this repetitive kind as well.

To test this ability, the solar cell was repeatedly illuminated at 100 mW cm^{-2} under open circuit, for the periods of 5 min, 10 min, and 20 min, representing the conditioning step with different relevance. After each light exposure, the device is rested in the dark for 20 min, representing the information loss phase. This 20 min resting period is chosen based on the observation that during this time, most of the J_{SC} is recovered (Figure 1F), in this way mimicking the so typical forgetting of the just learned information.

Figure 2A shows repetitive learning of the same DSC that has already undergone a one time learning at the short conditioning period of 5 min, as depicted in Figure 1C. With each illumination (conditioning) and resting in the dark (information loss) cycle, the recovered J_{SC} , electronically representing learning (filled squares), exhibits a slow decay, revealing that the cell is indeed learning with each conditioning and information loss cycle, albeit very slowly. The filled squares graph reflects this repetitive learning curve of the DSC. Note that after the 8th learning cycle, the J_{SC} in the learning curve starts to saturate. As discussed before, the gradual J_{SC} drop mirrors the ongoing learning process of the solar cell, whereas the J_{SC} saturation after the 8th learning cycle can be considered as the DSCs inability to further learn. In short, once the cell has reached its J_{SC} saturation, it has mastered the optical information. More remarkably, this saturated J_{SC} (last point in the learning curve in Figure 2A) recovers much slower with resting time in the dark as compared to the one time learning process (Figure 2B). Even after close to 200 h in the dark, the J_{SC} shows an approximate 1 mA cm^{-2} lower J_{SC} relative to the value prior to the repetitive learning process, whereas the J_{SC} has almost completely recovered after only 10 min in the dark after the one time learning method (filled circles graph in Figure 2B). This behavior discloses that our DSC stores the learned information longer the more often it is exposed to it, a trait similar to human learning.

As the conditioning time is extended to 10 min and 20 min, the J_{SC} after each illumination and resting cycle decays faster exponentially in comparison to the 5 min case (Figure 2C and 2E respectively). This trend implies that the more important the conditioning, the better the cell learns, following the notion that the larger the J_{SC} drops, the deeper the learning process. While this ΔJ_{SC} is comparable for both the 10 min and 20 min exposure interval after the first three learning cycles, the J_{SC} in the dark after the 2nd cycle starts to saturate in the case of 20 min illumination period (Figure 2E). This behaviour is not taking place for neither the 5 min nor the 10 min interval conditioning, indicating that at the longer 20 min conditioning, the cell is capable of swiftly mastering the input after just two learning cycles, therefore showing

signs of intelligent learning expressed in the ability to combine both the importance of the information (conditioning period) and the frequency of learning. In addition, akin to the 5 min illumination interval, the J_{SC} recovery after repetitive learning is significantly retarded in contrast to the one time exposure (Figure 2D, 2F), again highlighting the solar cell's ability to maintain the learned information for a prolonged time the more frequently the device learns.

In summary, a dye sensitized solar cell is fabricated whose short circuit photocurrent density J_{SC} can be manipulated depending on the illumination period. Strikingly, this J_{SC} slowly recovers back to its initial value once the light exposure is absent. Hereby, we found out that the longer the light stimulation lasts, the more retarded is the J_{SC} recovery. If one interprets the illumination duration as the conditioning for the importance of the incoming optical information, then the solar cell has the ability to intelligently distinguish between crucial data which it can retain for a longer time in terms of an extended J_{SC} retention with prolonged exposure period. Furthermore, the more often the device undergoes cycles of light exposure followed by resting in the dark, the longer the triggered J_{SC} drop can be maintained, indicating the cell's capability of repetitive learning. Therefore, our DSC exhibits important traits of perceptive smart learning that is reminiscent to human learning itself, opening possibilities for driving forward fully autonomous and energy saving artificially intelligent machines.

While certain of the preferred embodiments of the present invention have been described and specifically exemplified above, it is not intended that the invention be limited to such embodiments. Various modifications may be made thereto without departing from the scope and spirit of the present invention, as set forth in the following claims.

Example 2: Visual image recognition sensor based on learning photovoltaic cells

Current computer vision technology requires cameras with photo detectors to capture the seen images. Appropriate image recognition software analyzes these images and tries to associate them with known objects. That is, numerous redundant images have to be stored in the computer's memory. This data redundancy can be avoided by using the visually learning sensor (VLS) 1 shown in **Figure 3**, consisting of a plurality of learning solar cells 2 acting as pixels. This VLS autonomously decides which seen object should be learned/memorized based on exposure time and repetition cycles without any need for software instructions and wasted memory space. Object recognition is possible upon re-exposure of the learned object.

Therefore, this VLS can be used in robotics, self-navigating vehicles, or smart surveillance systems for autonomous learning of frequently occurring objects and their recognition.

The operation principle of the visually learning sensor (VLS) is illustrated in Figure 3: The visually learning sensor 2 consists of a matrix of our learning solar cells 2. Each solar cell acts as a pixel, with each pixel having a specific address communicating with the computer. Panel (a) illustrates the learning process. The VLS learns to recognize an object by being exposed to it for an extended period of time or repeatedly. Panel (b) illustrates memorization. Only those pixels illuminated by the object (dark grey squares) 2.1 during the learning process will memorize. Pixels /cells 2.2 which were not exposed to any different light change do not change their electronic behaviour. Panels (c) and (d) illustrate image recognition and absence of recognition, respectively. When illuminated by the same learned object, each of the pixels participating in the learning delivers a different current than those pixels that did not learn. These specific pixel currents correspond to the object learned, in this way enabling the computer to recognize the learned object. Regarding panel (d), when the VLS is illuminated by a not learned object, the pixel currents do not correspond to the learned object.

Example 3: Artificial neural synapses for self-evolving electronic circuits

The learning solar cells of the invention can be used as artificial optical/neural synapses. That is, the learning solar cells memorize after continued or repeated optical stimulation, akin to synapses in the human brain that learn to deliver altered currents after repeated voltage spike exposure. Networks of such optical neural synapses (Figure 4) represent self-evolving or adaptive electronic circuits in which changed behaviour of individual optical synapses (due to optical stimuli) influence the overall output signal. The optical neural network shown in Figure 4 for instance can be used as an optical perceptron. Such optical neural networks can be used for optical computing, learning, and sensing.

Figure 4 is a schematic of an optical neural network 100 consisting of optical synapses comprised of our learning solar cells 10, 20. The overall output current J_{Out} depends on the sum of the individual currents delivered by each optical synapse. Each optical synapse that has undergone visual learning 10 (black squares) delivers a different current J_{Learn} as compared to the not influenced synapses 20 (grey squares).

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Claims

1. A photoelectronic and/or optoelectronic learning device and/or memory device, which has an electronic property, wherein a value of said electronic property changes as a function
5 of duration of a conditioning phase and/or as a function of light intensity during said conditioning phase, in which conditioning phase the device is exposed to an optical stimulus, and wherein said device is susceptible of exhibiting an information loss phase subsequent to said conditioning phase, said information loss phase being characterized by the absence of conditioning and/or light stimulus, wherein, during said information loss phase, said value of
10 said property changes with opposite sign compared to said conditioning phase, such that the value of said electronic property changes in direction of a starting point value as a function of time during said information loss phase.
2. The device of claim 1, which is a hardware based device and/or which can operate in
15 the absence of any program code and/or software.
3. The device of any one of claims 1-2, wherein said value of said electronic property changes from a starting point value at the beginning of said conditioning phase to an end point value at the end of said conditioning phase, wherein said change is a function of time and/or
20 of light intensity during said conditioning phase, and wherein the end point value is different from said starting point value.
4. The device of any one of claims 1-3, wherein a value of said property is an inherent
25 property of the device at a given moment in time.
5. The device of any one of claims 1-4, wherein said value of said property is the consequence and/or affected by previous conditioning and absence of conditioning.
6. The device of any one of the preceding claims, which has a property, wherein a value
30 of said property is susceptible of changing as a consequence or function of repeated cycles of conditioning and absence of conditioning.
7. The device of any one of the preceding claims, wherein an Nth starting point value of said electronic property at the beginning of an Nth conditioning phase is different from an

(N+1)th starting point value of said electronic property at the end of an Nth information loss phase, the information loss phase being characterized by the absence of conditioning.

8. The device of any one of the preceding claims, wherein an Nth starting point value of said electronic property at the beginning of an Nth conditioning phase is different from an (N+1)th starting point value of said electronic property at the beginning of an (N+1)th conditioning phase.

9. The device of any one of the preceding claims, which is a photoelectric conversion device, preferably a dye-sensitized solar cell.

10. The device of claim 9, which is a dye sensitized solar cell comprising an electrolyte comprising Co^{II+} and Co^{III+} cobalt complexes forming a redox couple, wherein, in said electrolyte, said Co^{II+} complex is present at a concentration smaller than the concentration of said Co^{III+} complex.

11. The device of claim 10, wherein said Co^{II+} complex is present at a concentration of ≤ 0.20 M and the Co^{III+} complex is present at a concentration of ≥ 0.1 M, preferably said Co^{II+} complex is present at a concentration of ≤ 0.15 M and the Co^{III+} complex is present at a concentration of ≥ 0.15 M.

12. The device of any one of the preceding claims, wherein said property is the short circuit current density (J_{SC}) of the device, and wherein a degree of a J_{SC} drop depends on how long the device is being illuminated.

13. The device of claim 12, wherein said degree of J_{SC} drop depends on the number of cycles of successive illumination and absence of illumination.

14. A photoswitch and/or a sensor comprising the device of any one of claims 1-13.

15. Use of the device of any one of the preceding claims in robotics, in particular as sensor or artificial intelligent eye for robotics, self-navigating vehicles, surveillance systems and self-evolving optoelectronic/electrochemical circuits and networks.

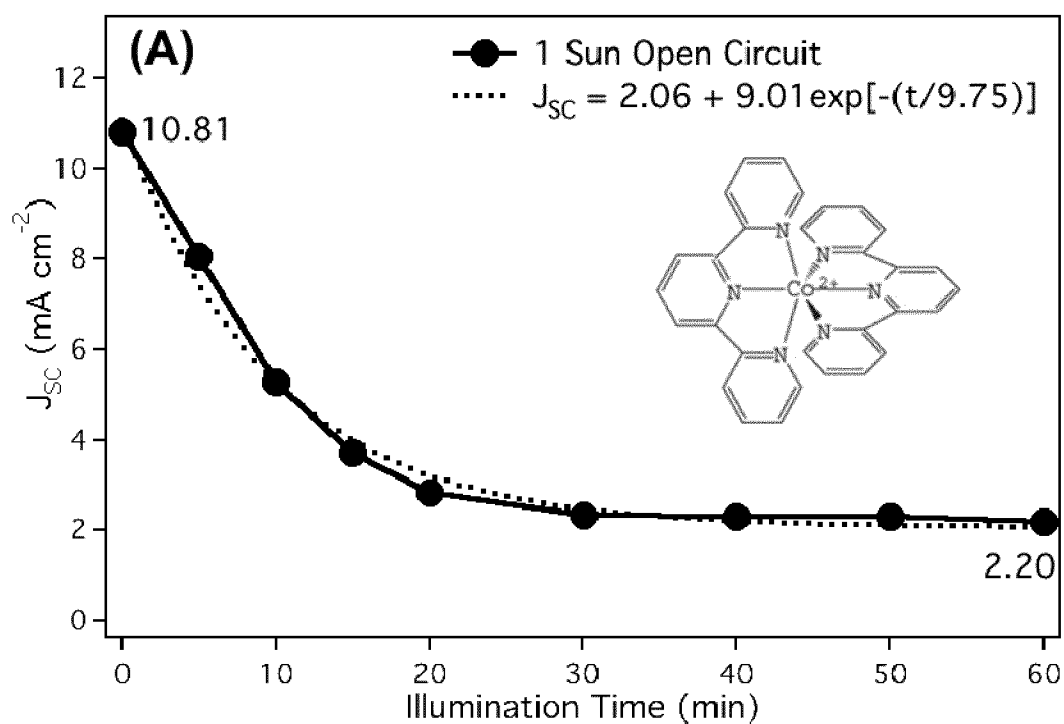


Figure 1 A

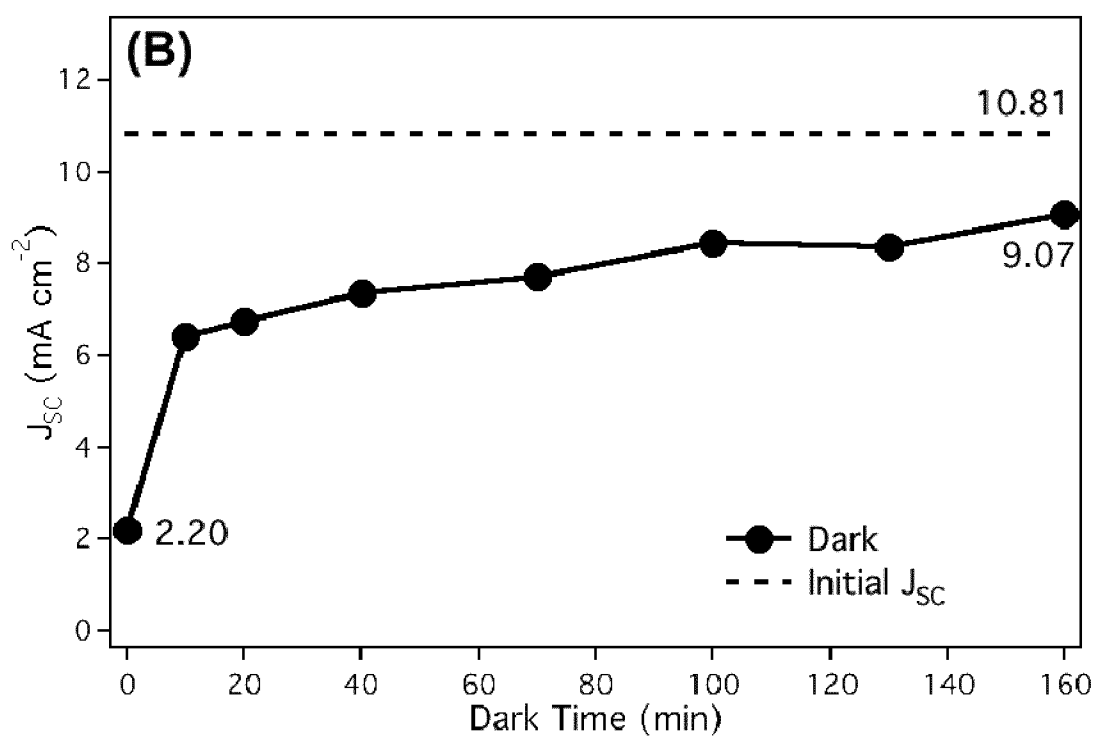


Figure 1 B

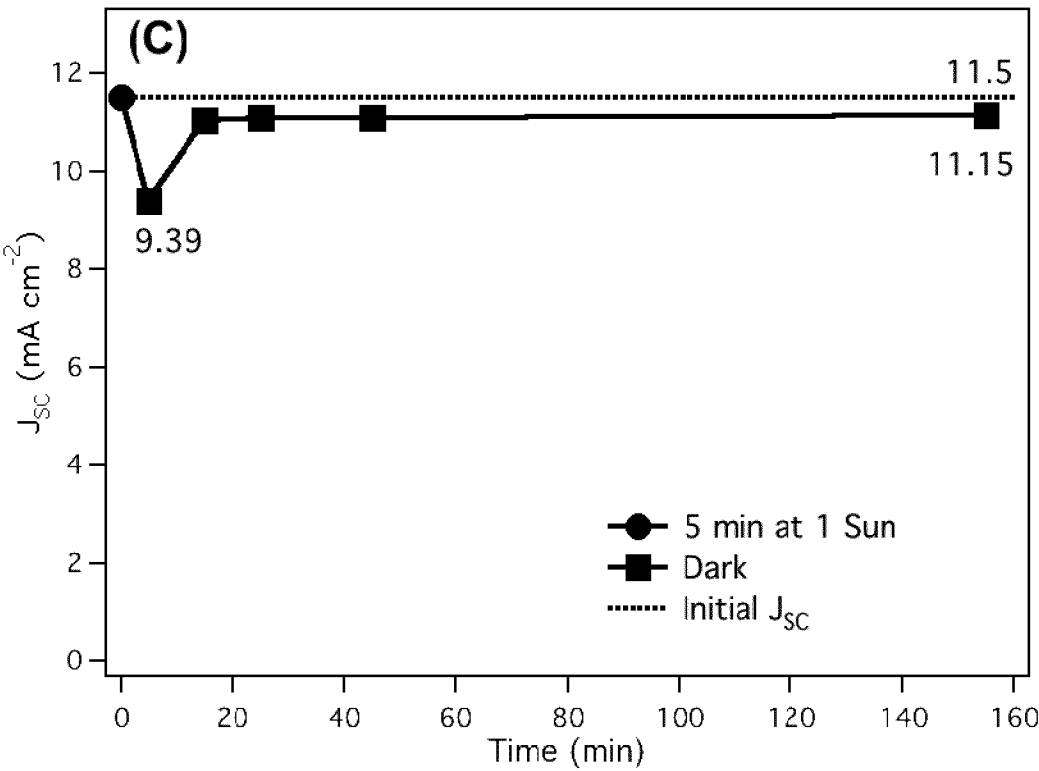


Figure 1 C

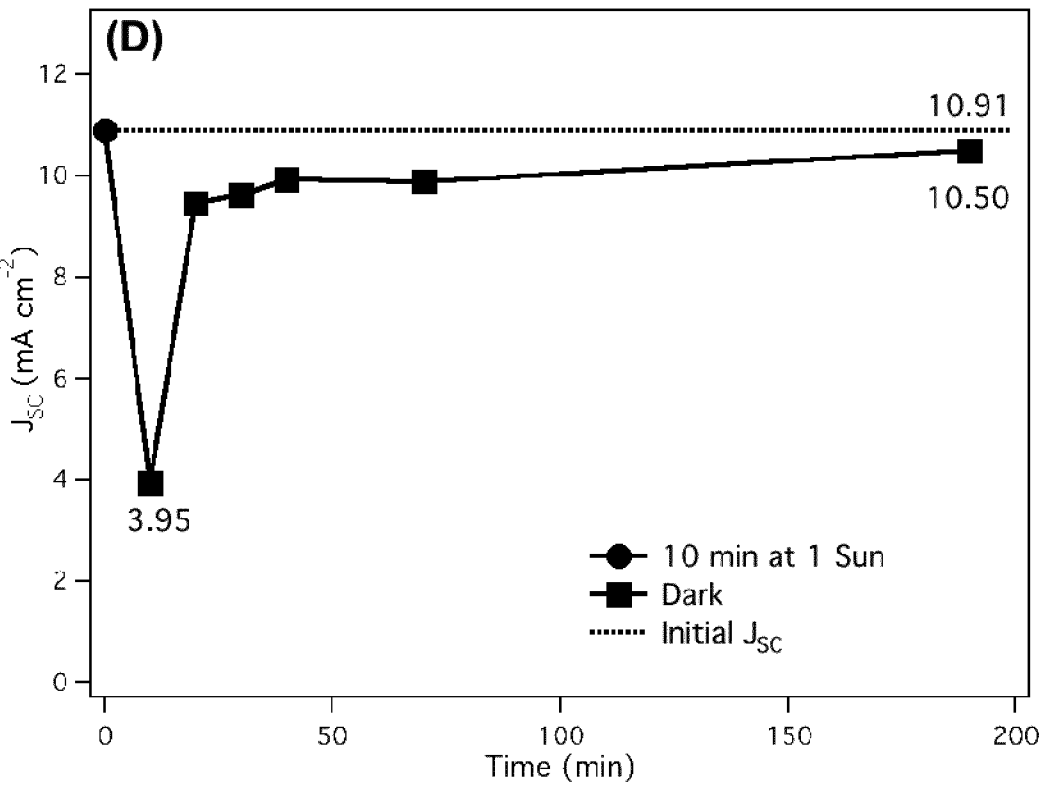


Figure 1 D

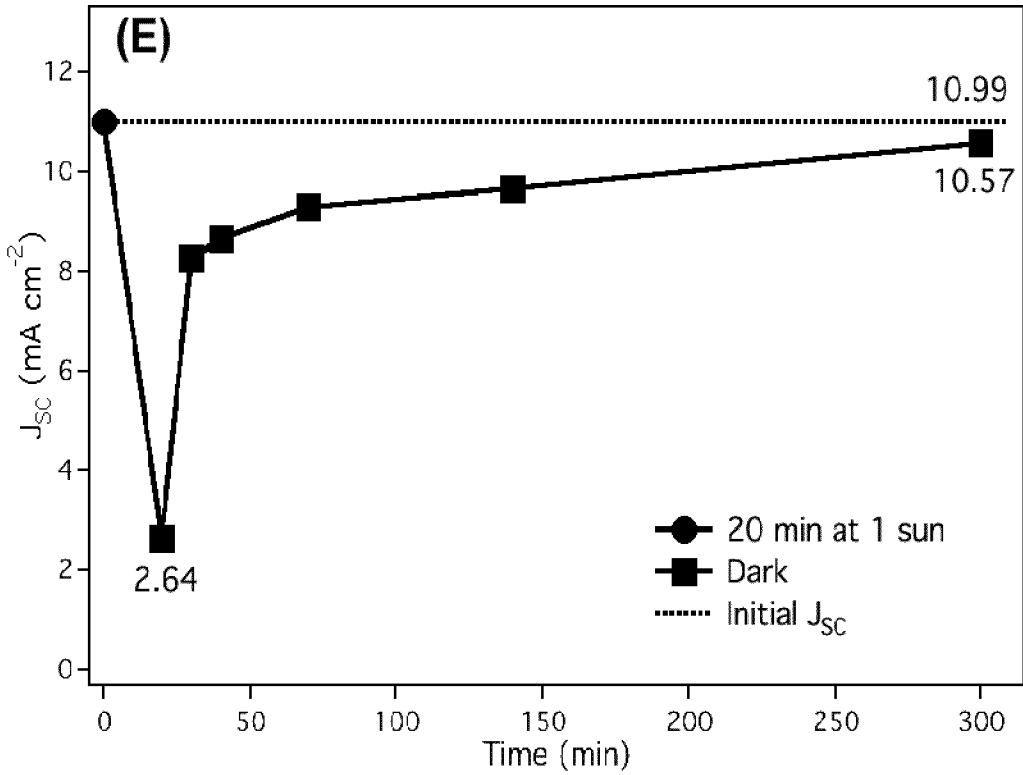


Figure 1 E

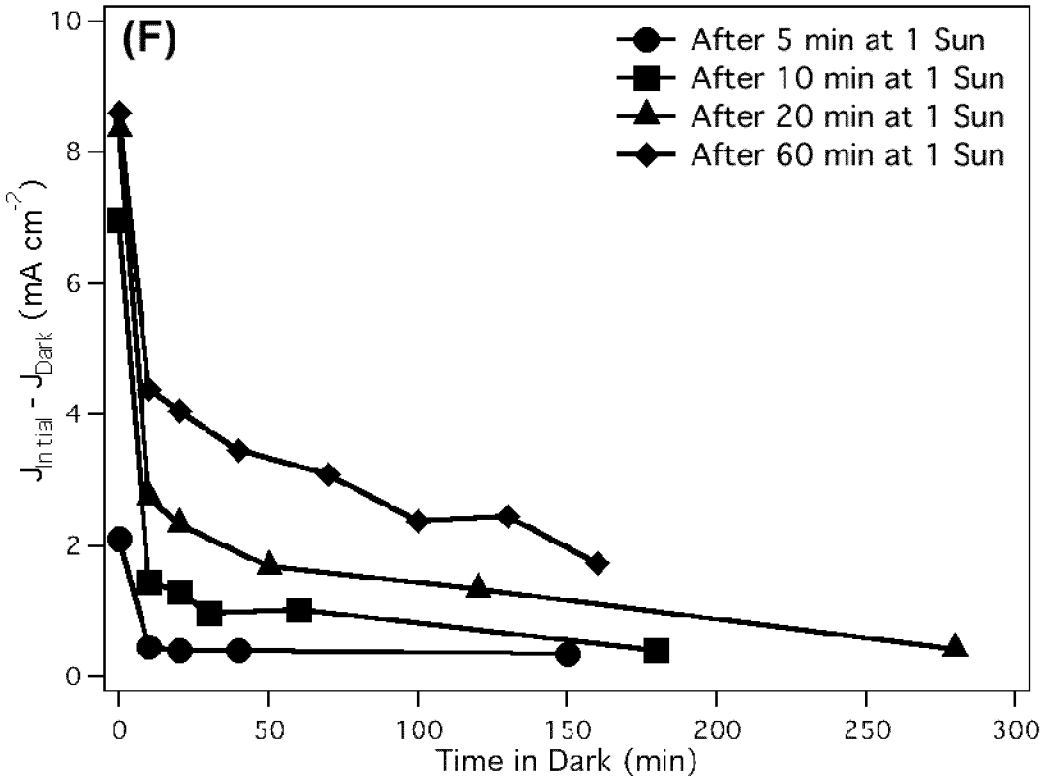


Figure 1 F

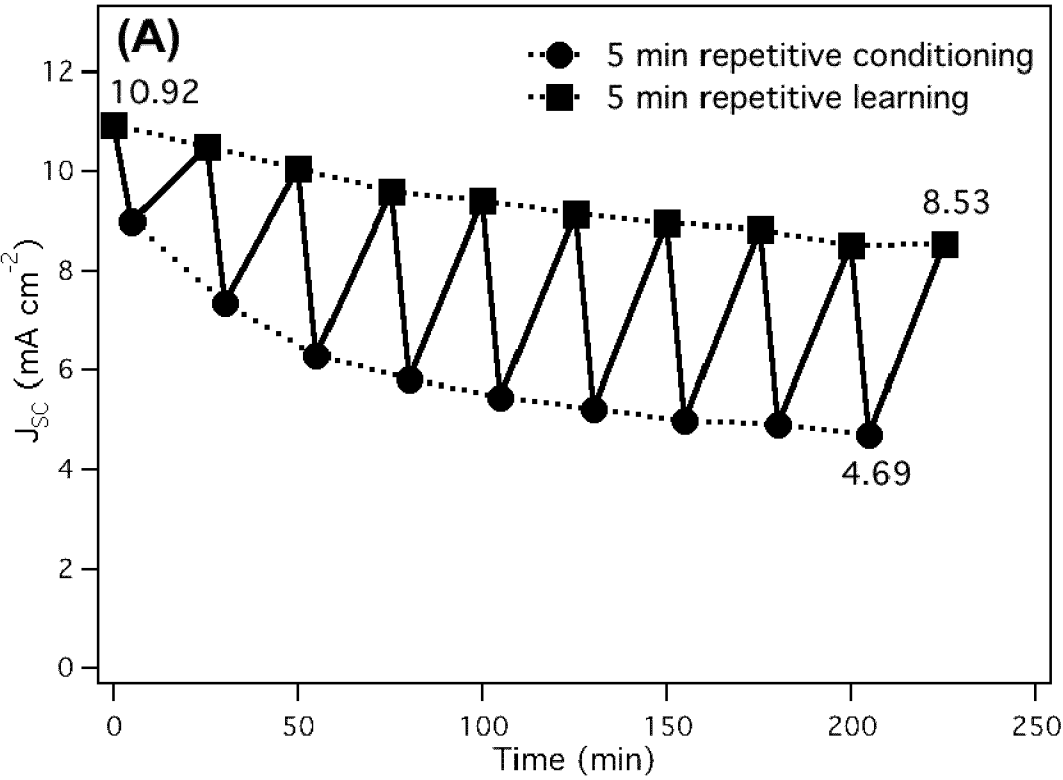


Figure 2 A

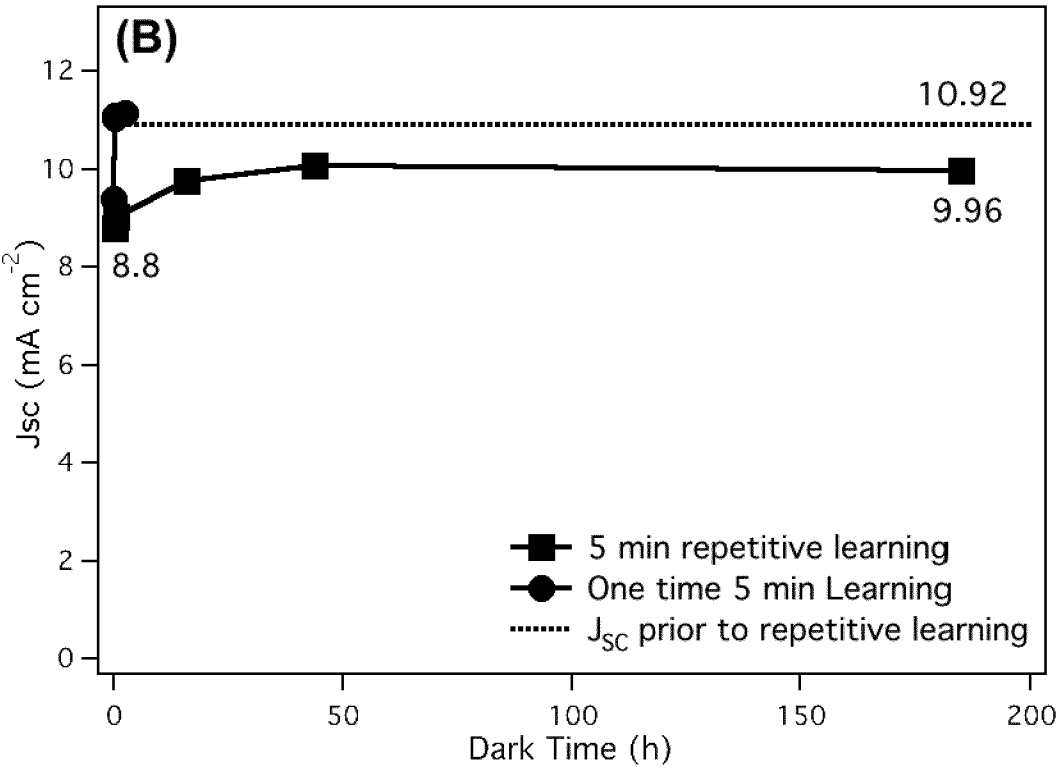


Figure 2 B

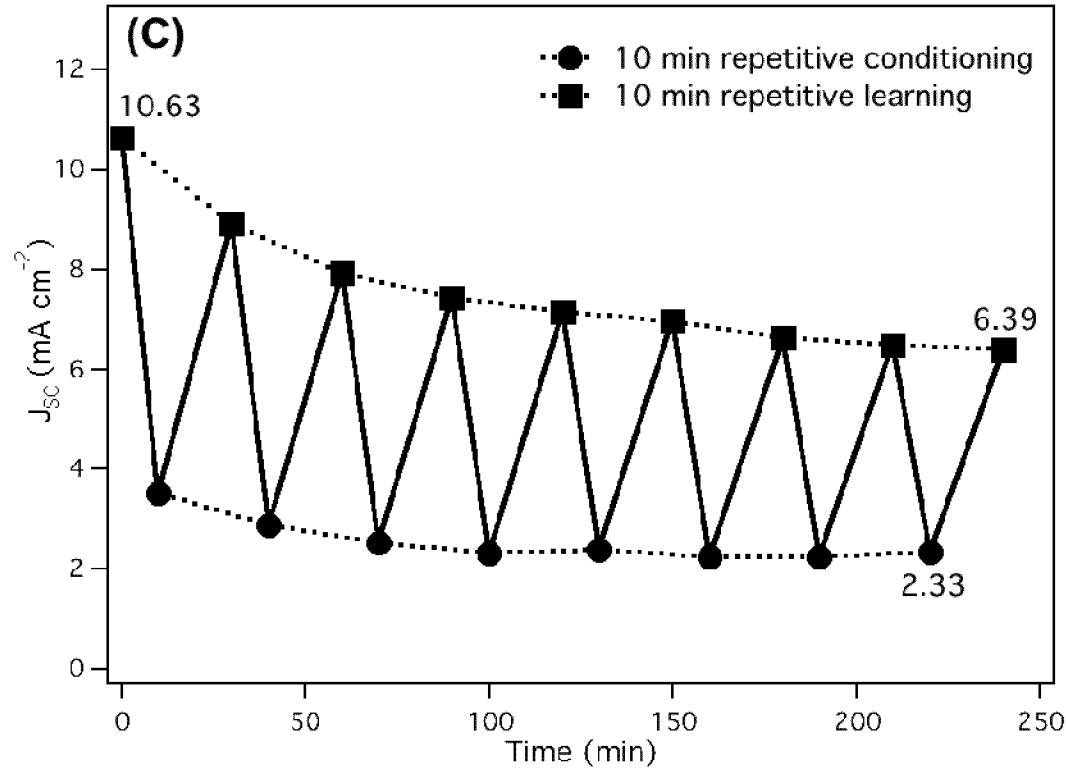


Figure 2 C

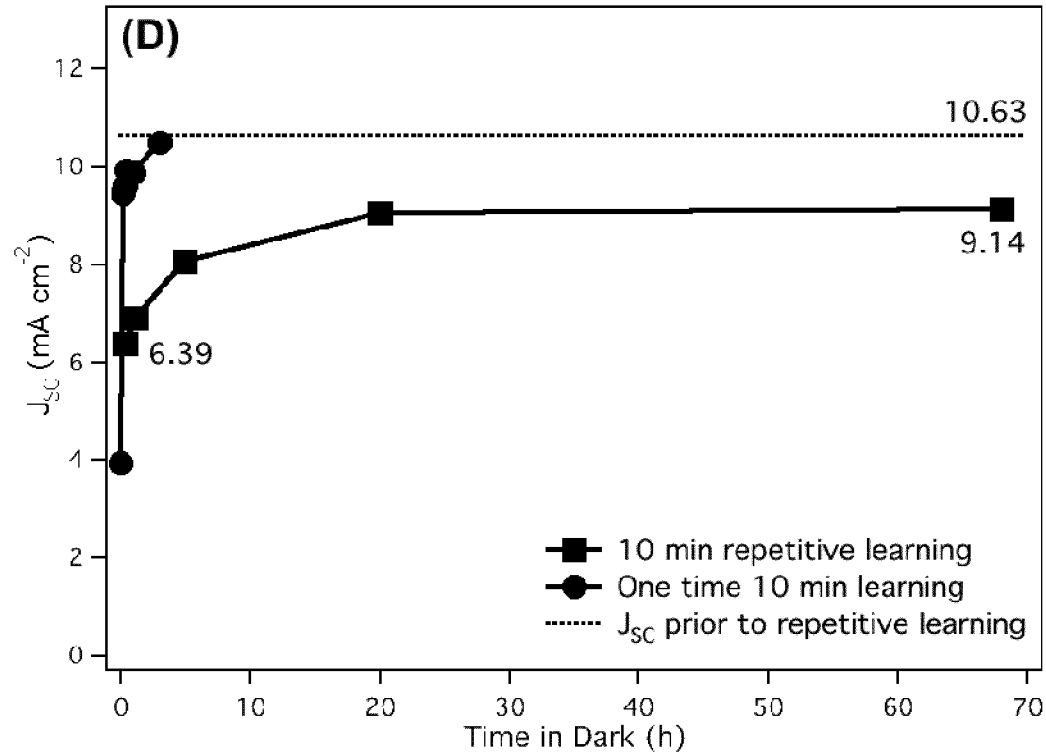


Figure 2 D

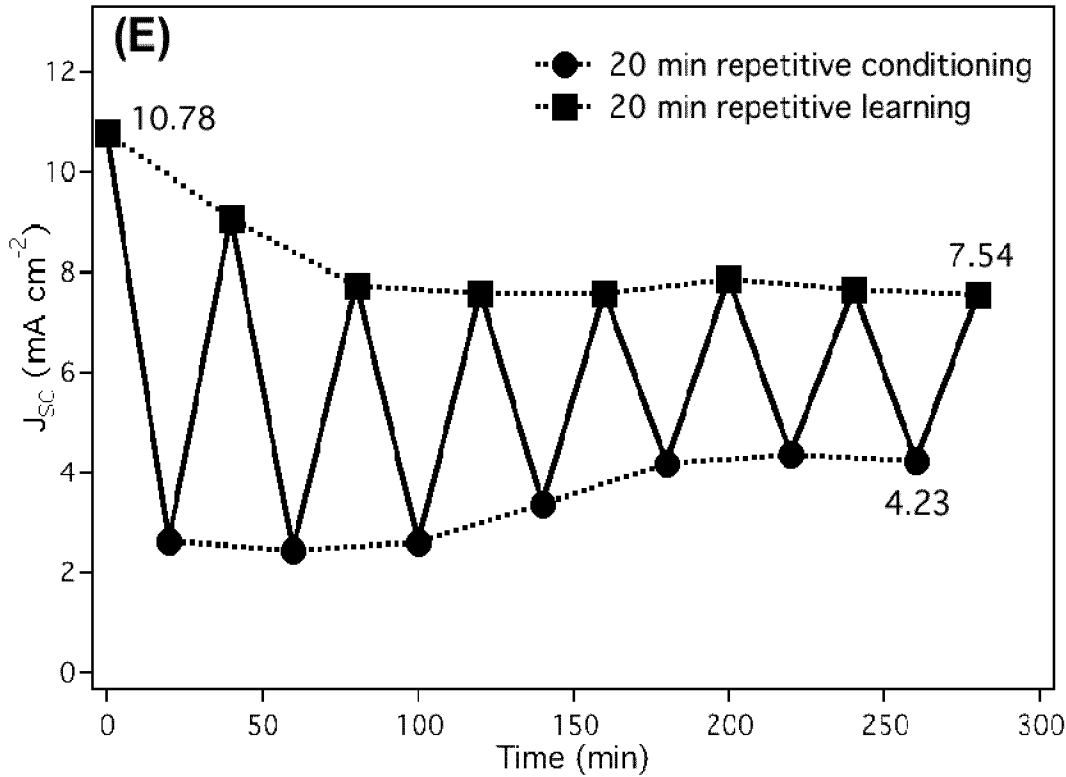


Figure 2 E

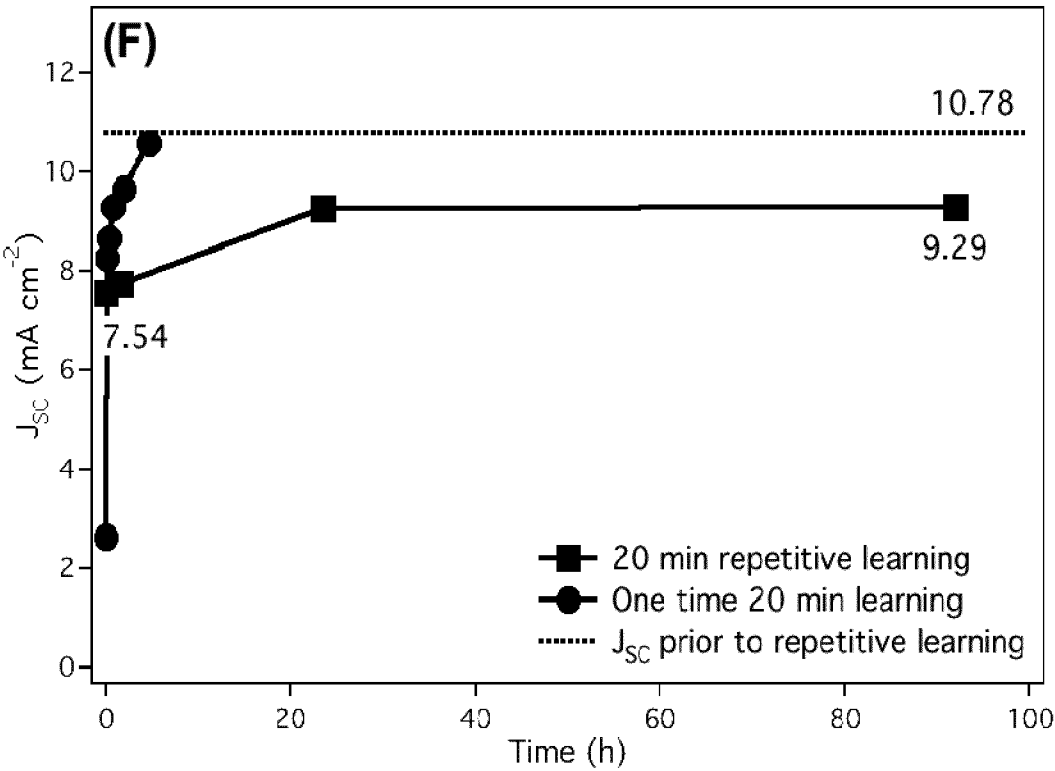


Figure 2 F

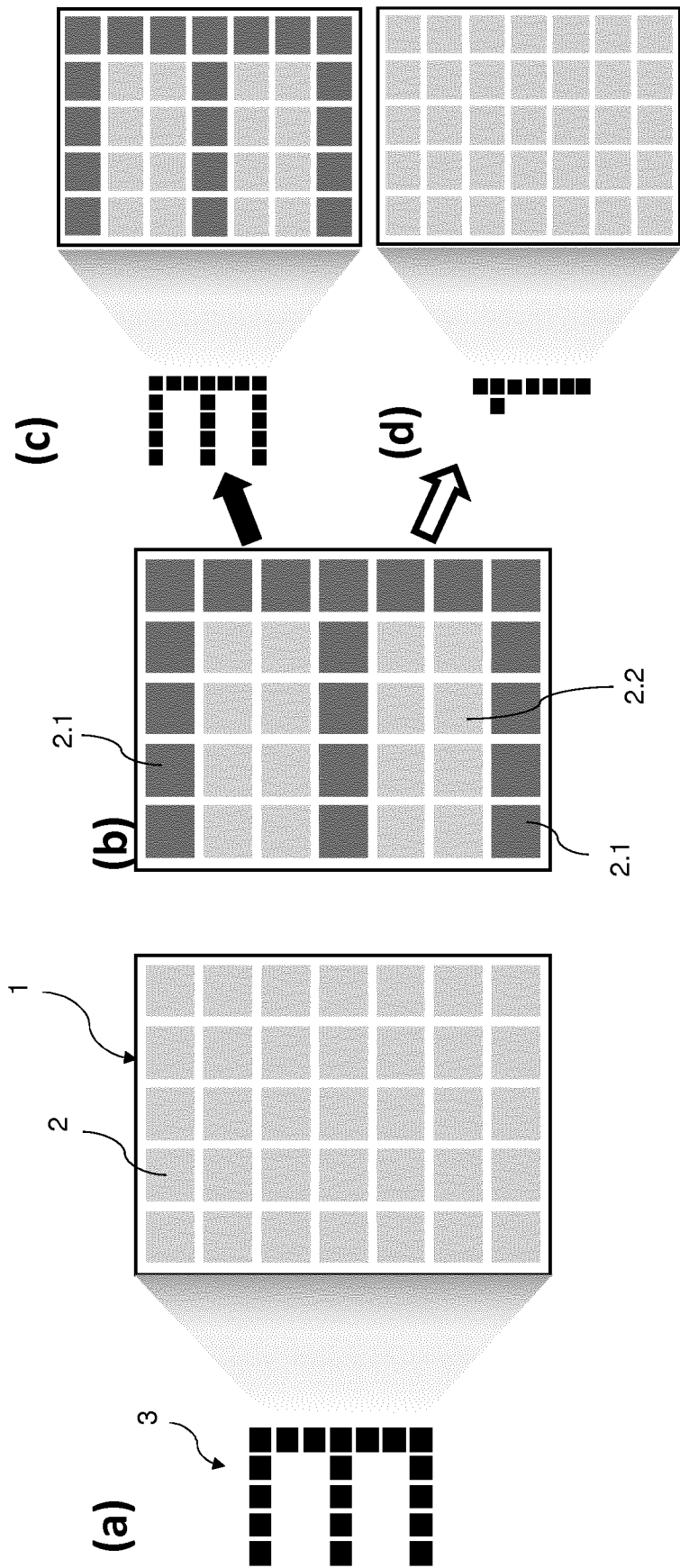


Figure 3

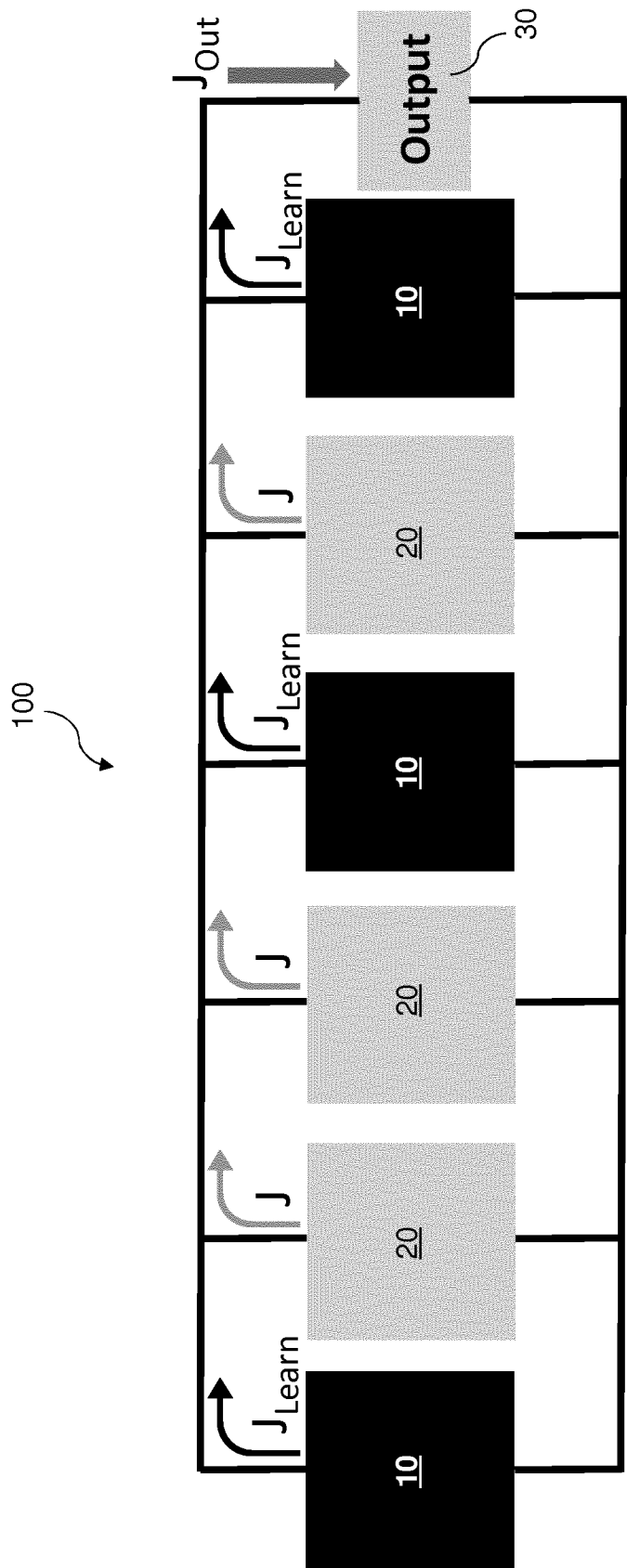


Figure 4