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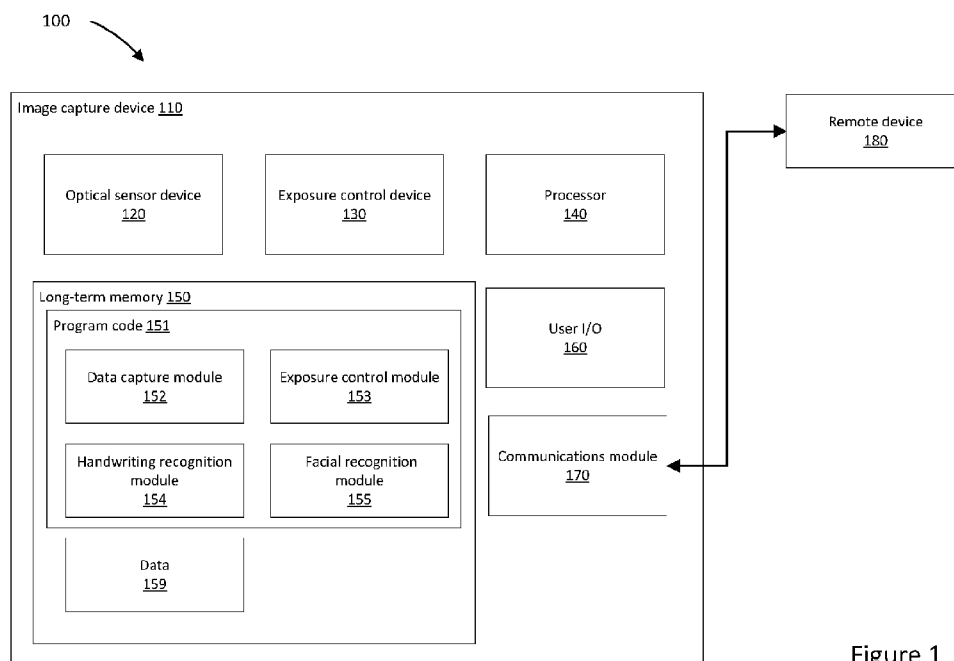


Figure 1

(57) Abstract: Described embodiments generally relate to an imaging device for capturing image data. The imaging device comprises an optical sensor responsive to electromagnetic radiation, wherein the sensor exhibits a photo-memory effect causing the sensor to act as a short-term memory device; an exposure control device configured to adopt a first mode and a second mode, wherein in the first mode the exposure control device causes electromagnetic radiation to reach the sensor and in the second mode the exposure control device restricts electromagnetic radiation from reaching the sensor; a processor configured to receive sensor data from the sensor, and to cause the exposure control device to selectively adopt the first mode and the second mode; and a long term memory device accessible to the processor, wherein the processor is configured to read executable instructions from the long term memory and to write sensor data to the long term memory. Data stored in the sensor acting as a short-term memory device is erasable by exposing the photo-sensor

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to electromagnetic radiation.

"Systems and methods for data storage and processing"

Technical Field

Embodiments generally relate to systems and methods for data storage and processing. In particular, embodiments relate to systems and methods for optoelectronic data storage and processing.

Background

Processes for capturing, storing and processing images are used in a number of industries and fields. In many cases, it is advantageous for the image capture, storage and processing to occur quickly. However, known processes often require transferring images between an image capture device such as a camera to a separate processing device such as a computer before image processing can occur. This introduces delays and inefficiencies which can negatively impact many computer vision applications which require rapid and close to real-time processing, including neuro-robotics, human-machine interaction technologies and bionic systems.

It is desired to address or ameliorate one or more shortcomings or disadvantages associated with prior systems and methods for data storage and processing, or to at least provide a useful alternative thereto.

Throughout this specification the word "comprise", or variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated element, integer or step, or group of elements, integers or steps, but not the exclusion of any other element, integer or step, or group of elements, integers or steps.

Any discussion of documents, acts, materials, devices, articles or the like which has been included in the present specification is not to be taken as an admission that any or all of these matters form part of the prior art base or were common general knowledge in the field relevant to the present disclosure as it existed before the priority date of each of the appended claims.

Summary

Some embodiments relate to an imaging device for capturing image data, the imaging device comprising:

an optical sensor responsive to electromagnetic radiation, wherein the sensor exhibits a photo-memory effect causing the sensor to act as a short-term memory device;

an exposure control device configured to adopt a first mode and a second mode, wherein in the first mode the exposure control device causes electromagnetic radiation to reach the sensor and in the second mode the exposure control device restricts electromagnetic radiation from reaching the sensor;

a processor configured to receive sensor data from the sensor, and to cause the exposure control device to selectively adopt the first mode and the second mode; and

a long term memory device accessible to the processor, wherein the processor is configured to read executable instructions from the long term memory and to write sensor data to the long term memory;

wherein data stored in the sensor acting as a short-term memory device is erasable by exposing the photo-sensor to electromagnetic radiation.

In some embodiments, the optical sensor is responsive to one or more of ultraviolet light, visible light, and infrared light.

According to some embodiments, the optical sensor comprises a two-dimensional semiconductor. In some embodiments, the two-dimensional semiconductor comprises at least one of an elemental material, transitional metal oxide, or transition metal chalcogenide. In some embodiments, the two-dimensional semiconductor comprises black phosphorous.

According to some embodiments, the optical sensor comprises an array of optical sensor devices.

In some embodiments, the sensor device is configured to exhibit a reference conductance in the absence of electromagnetic radiation, and to exhibit a wavelength dependent increase and/or decrease in conductance when exposed to electromagnetic radiation. In some embodiments, the conductance of the sensor device is configured to return to the reference conductance not less than 1 second after exposure to the electromagnetic radiation has ceased. In some embodiments, the conductance of the sensor device is configured to return to the reference conductance not less than 1 minute after exposure to the electromagnetic radiation has ceased.

According to some embodiments, the conductance of the sensor device increases when the sensor device is exposed to electromagnetic radiation of a first wavelength, and decreases when the sensor device is exposed to electromagnetic radiation of a second
5 wavelength. According to some embodiments, the first wavelength is between 250 and 315 nm, and the second wavelength is between 315 and 400 nm.

In some embodiments, the processor is configured to read data stored on the sensor device by applying a voltage to the sensor device.

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According to some embodiments, the exposure control device comprises at least one of a shutter configured to block electromagnetic radiation or a filter configured to filter out at least some wavelengths of electromagnetic radiation.

15 According to some embodiments, the exposure control device comprises at least one source of electromagnetic radiation.

Some embodiments relate to a method of capturing image data, the method comprising:
operating an exposure control device to adopt a first mode, wherein in
20 the first mode the exposure control device causes an optical sensor responsive to electromagnetic radiation to be exposed to first electromagnetic radiation, wherein the sensor exhibits a photo-memory effect causing the sensor to act as a short-term memory device;

upon determining that a threshold period of time has elapsed, operating
25 the exposure control device to adopt a second mode, wherein in the second mode the exposure control device causes the sensor to be blocked from electromagnetic radiation;

reading data captured by the sensor based on the exposure; and
recording the read data to a long term memory device.

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In some embodiments, the method is performed by the device of some other described embodiments.

Some embodiments further comprise erasing the read data from the sensor acting as a
35 short term memory device by operating the exposure control device to adopt a third

mode, wherein in the third mode the exposure control device causes the sensor to be exposed to second electromagnetic radiation.

5 In some embodiments, the exposure control device comprises a shutter or filter, wherein adopting a first mode comprises opening the shutter or filter, and wherein adopting the second mode comprises closing the shutter or filter.

10 In some embodiments, the exposure control device comprises a source of electromagnetic radiation, wherein adopting a first mode comprises switching on the source of electromagnetic radiation, and wherein adopting the second mode comprises switching off the source of electromagnetic radiation.

15 According to some embodiments, reading data captured by the sensor comprises applying a voltage to the sensor.

Some embodiments relate to a method of training a neural network, the method comprising:

20 receiving at least one training image and a label related to the at least one training image;
capturing image data by performing the method of some other embodiments, wherein the first electromagnetic radiation is generated based on the at least one training image; and
determining an output based on the read data and a weight matrix;
comparing the read data with the label; and
25 modifying the weight matrix based on the comparison.

Some embodiments further comprise repeating the method with the same at least one training image.

30 Some embodiments further comprise repeating the method with a further training image different to the at least one training image.

Brief Description of Drawings

35 Embodiments are described in further detail below, by way of example and with reference to the accompanying drawings, in which:

Figure 1 shows a block diagram of a system for data storage and processing according to some embodiments;

Figure 2 shows a detailed view of an optical sensor device of Figure 1;

Figures 3A and 3B show graphs illustrating write and erase functions of the optical sensor device of Figure 2;

Figures 4A, 4B and 4C illustrating write, erase and read functions of the optical sensor device of Figure 2;

Figures 5A, 5B and 5C show graphs illustrating the optical sensor device of Figure 2 acting as multi-bit memory;

Figures 6A and 6B show transfer function of the optical sensor device of Figure 2;

Figures 7A and 7B show the optical sensor device of Figure 2 acting as short and long term memory;

Figure 8 shows a method of training the optical sensor device of Figure 2 for handwriting recognition;

Figures 9A and 9B show the results of optical sensor device of Figure 2 after the method of Figure 8;

Figure 10 shows a method of training the optical sensor device of Figure 2 for facial recognition;

Figure 11 shows the results of optical sensor device of Figure 2 after the method of

Figure 10 is performed with varying parameters;

Figure 12 shows a flowchart illustrating a method of training the system of Figure 1 to perform image recognition according to some embodiments; and

Figure 13 shows a flowchart illustrating a method of capturing image data using the imaging device of Figure 1.

Detailed Description

Embodiments generally relate to systems and methods for data storage and processing. In particular, embodiments relate to systems and methods for optoelectronic data storage and processing.

Conventionally in image capture devices such as cameras, a photo-sensor is used to generate electrical signals based on exposure to light. The photo-sensor cannot store the captured image data, as conventional photo-sensors exhibit fast recovery of photo-response after light is switched off. To store the data, the electrical signals are read by an auxiliary circuit and data is stored to a separate electronic memory device in the form of “1”s and “0”s which are associated with the conductance states of the

electronic memory. The two data states can be manipulated by way of write and erase procedures, where a write procedure causes a memory location to take on a “1” state and an erase procedure causes the device to take on a “0” state. These write and erase procedures are performed electronically by changing or switching the conductance of the memory locations in the memory device. However, the use of electronically programmable memory devices can result in processing delays. They generate large amounts of redundant data which requires significant computing to extract meaningful information, and also require a large amount of data storage. These requirements result in increased data latency and high power consumption. Furthermore, electrical signals induce electronic noise in circuits, which can affect the performance and accuracy of data processing and neuromorphic processes.

In contrast, described embodiments relate to systems and methods for data storage and processing that make use of a sensor exhibiting a fully light controlled memory effect, that allows for data to be both written and erased optically by way of exposure to electromagnetic radiation such as light. This sensor can therefore be controlled without relying on the application of alternating polarity electric signals. This is made possible by using a sensor element exhibiting a persistent photocurrent in the absence of exposure to electromagnetic radiation such as light, having slower recovery of photo-response than conventional photo-sensors. Furthermore, these embodiments allow for in-pixel data storage and processing, meaning processing can occur within the optical sensor capturing the data, without requiring the data to be transferred to an electronic memory device. The sensor can therefore act as both a light sensor and a memory device. This may allow for faster data processing speeds due to high bandwidth, low parasitic crosstalk and ultralow power consumption as well as high scalability. This may allow for processes such as neuromorphic pre-processing and image recognition, visual memory, wavelength selective multi-bit programming, and in-pixel image pre-processing, for example. These processes may be applied to industries including automation, security and surveillance, brain-machine interface and bionics, among others.

Figure 1 shows a block diagram of a system 100 for capturing, storing and processing image data according to some embodiments.

System 100 comprises an imaging device, being image capture device 110. Image capture device 110 may comprise a camera or scanner device in some embodiments.

According to some embodiments, image capture device 110 may be configured to act as a neuromorphic imaging device that may be used within photonic neuromorphic circuits and artificial visual systems, for example.

- 5 Device 110 includes an optical sensor device 120, which may be configured to also act as a short term memory device, as described in further detail below. Optical sensor device 120 may comprise at least one semiconductor in some embodiments. According to some embodiments, optical sensor device 120 may comprise an array of semiconductors acting as pixels for capturing an array of image data.

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Optical sensor device 120 may be sensitive to electromagnetic radiation. According to some embodiments, optical sensor device 120 may be sensitive to particular wavelengths of electromagnetic radiation. For example, in some embodiments, optical sensor device 120 may be sensitive to light. In some embodiments, optical sensor device 120 may be sensitive to visible light. Optical sensor device 120 may be sensitive to light with wavelengths between 300nm and 800nm, for example. In some embodiments, optical sensor device 120 may be sensitive to one or more of ultraviolet light, visible light, and/or infrared light. Optical sensor device 120 may be sensitive to light with wavelengths between 280nm and 1300nm, for example.

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- 20 In some embodiments, optical sensor 120 may comprise at least one two-dimensional semiconductor or semiconductor array. In some embodiments, optical sensor 120 may comprise at least one two-dimensional semiconductor or semiconductor array comprising an elemental material, such as black phosphorous, for example. In some embodiments, optical sensor 120 may comprise at least one two-dimensional semiconductor or semiconductor array comprising a transitional metal oxide, such as molybdenum trioxide, for example. In some embodiments, optical sensor 120 may comprise at least one two-dimensional semiconductor or semiconductor array comprising a transition metal chalcogenide, such as tin sulphide (SnS) or molybdenum disulphide (MoS₂), for example.

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According to some embodiments, the semiconductor may be the two-dimensional black phosphorous semiconductor described in International Application No. PCT/AU2019/050662, the entirety of which is herein incorporated by reference.

- 35 According to some embodiments, the optical sensor device 120 may exhibit a reference conductance when not exposed to electromagnetic radiation such as light, and may

exhibit wavelength dependent increase and decrease in conductance when exposed to particular wavelengths of electromagnetic radiation. The conductance exhibited by the optical sensor device 120 may increase when exposed to electromagnetic radiation of a first wavelength, and decrease when exposed to electromagnetic radiation of a second wavelength. For example, according to some embodiments, the conductance exhibited by optical sensor device 120 may increase when exposed to light with a wavelength in the range of 250 – 315 nm, and may decrease when exposed to light with a wavelength in the range of 315 – 400 nm. Write and erase procedures can therefore be performed on optical sensor device 120 by exposing optical sensor device 120 to particular electromagnetic radiation wavelengths, and without using electronic write or erase procedures.

According to some embodiments, after exposure to the electromagnetic radiation has stopped, optical sensor device 120 may exhibit optical memory, with conductance persisting in the absence of electromagnetic radiation, allowing optical sensor device 120 to act as a short-term memory device. According to some embodiments, optical sensor device 120 may exhibit a photocurrent for over 1 second after exposure to electromagnetic radiation has stopped. According to some embodiments, optical sensor device 120 may exhibit a photocurrent for over 1 minute after exposure to electromagnetic radiation has stopped. According to some embodiments, optical sensor device 120 may exhibit a photocurrent for over 10 minutes after exposure to electromagnetic radiation has stopped. According to some embodiments, optical sensor device 120 may exhibit a photocurrent for over 1 hour after exposure to electromagnetic radiation has stopped. According to some embodiments, optical sensor device 120 may exhibit a photocurrent for over 5 hours after exposure to electromagnetic radiation has stopped.

Image capture device 110 may also comprise an exposure control device 130, to control the exposure of optical sensor device 120 to light or to particular wavelengths of electromagnetic radiation. According to some embodiments, exposure control device 130 may comprise at least one of a shutter, filter or lens. According to some embodiments, exposure control device 130 may comprise one or more light sources. For example, exposure control device 130 may comprise a first light source producing light having a first wavelength that increases the conductance of or otherwise produces a write effect on optical sensor device 120, and a second light source producing light having a second wavelength that decreases the conductance of or otherwise produces

an erase effect on optical sensor device 120. Exposure control device 130 may be located proximate to optical sensor device 120.

Image capture device 110 further comprises a processor 140, which may comprise one or more microprocessors, central processing units (CPUs), application specific instruction set processors (ASIPs), or other processor capable of reading and executing instruction code. According to some embodiments, processor 140 may be located on a single chip with optical sensor device 120. According to some embodiments, processor 140 may also be located on a single chip with long-term memory 150. Processor 140 may be configured to control the operation of exposure control device 130 to write and erase data from optical sensor device 120. Processor 140 may also be configured to read data from optical sensor device 120. According to some embodiments, reading data from optical sensor device 120 may comprise applying a voltage to optical sensor device 120 and determining a conductance or resistance of the device based on the applied voltage.

Image capture device 110 may further comprise long-term memory 150 storing program code 151 and data 159. Processor 140 may be configured to access long-term memory 150, to execute instructions stored in program code 151 and to read from and write to data 159. According to some embodiments, processor 140 may be configured to read data from optical sensor device 120 and write the data to data 159 of long-term memory 150 for long term storage. Long-term memory 150 may comprise one or more volatile or non-volatile memory types, such as RAM, ROM, EEPROM, or flash, for example.

Program code 151 of long-term memory 150 may comprise a plurality of code modules executable by processor 140 to cause image capture device 110 to capture, store and process image data. For example, program code 151 may include a data capture module 152, an exposure control module 153, a handwriting recognition module 154 and a facial recognition module 155.

When processor 140 executes data capture module 152, processor 140 may be caused to apply a voltage to optical sensor device 120, determine at least one conductance of optical sensor device 120, and to write data to data 159 based on the at least one conductance.

When processor 140 executes exposure control module 153, processor 140 may be caused to control the functions of exposure control device 130. Where exposure control device 130 comprises a shutter, the control may include opening and/or closing the shutter, for example. Where exposure control device 130 comprises a light source, the control may include turning the light source on and off.

When processor 140 executes handwriting recognition module 154, processor 140 may be caused to control cause optical sensor device 120 to act as a neural network, and to train optical sensor device 120 to recognise images of handwritten characters, as described below in further detail with reference to Figure 8 and 9.

When processor 140 executes facial recognition module 155, processor 140 may be caused to control cause optical sensor device 120 to act as a neural network, and to train optical sensor device 120 to recognise images of faces, as described below in further detail with reference to Figures 10 and 11.

Image capture device 110 further includes user I/O 160, which may include one or more forms of user input and/or output devices, such as one or more of a screen, keyboard, mouse, touch screen, microphone, speaker, or other device that allows information to be delivered to or received from a user. Image capture device 110 may also include communications module 170. Communications module 170 may be configured to communicate with one or more external computing devices or computing systems, via a wired or wireless communication protocol. For example, communications module 170 may facilitate communication via at least one of Wi-Fi, Bluetooth, Ethernet, USB, or via a cellular network in some embodiments. In the illustrated embodiment, communications module 170 is in communication with a remote device 180, which may be a computer in some embodiments.

Figure 2 shows a detailed view of optical sensor device 120 with exposure control device 130. In the illustrated embodiments, exposure control device 130 comprises two light sources 132 and 134, with light source 132 producing light with a 280nm wavelength and light source 134 producing light with a 365nm wavelength. However, as described above, exposure control device 130 may comprise a different mechanism for selectively exposing optical sensor device 120 to light or other electromagnetic radiation. For example, exposure control device 130 may comprise a first filter for filtering electromagnetic radiation of a first wavelength, a second filter for filtering

electromagnetic radiation of a second wavelength and a shutter for blocking all electromagnetic radiation. Processor 140 manipulating exposure control device 130 may therefore be able to cause only electromagnetic radiation of the first wavelength, only electromagnetic radiation of the second wavelength, or no electromagnetic radiation to be received by optical sensor device 120.

Optical sensor device 120 may comprise an optoelectronic memory device fabricated in a phototransistor configuration as described in International Application No. PCT/AU2019/050662. In the embodiment illustrated in Figure 2, optical sensor device 120 comprises a sensing element 121, which may be a black phosphorous layer comprising multiple vertically stacked layers of black phosphorous. According to some embodiments, sensing element 121 may be comprise an atomically thin semiconductor material. According to some embodiments, the thickness of the semiconductor material may be in the range of 2nm to 50 nm. According to some embodiments, this may be produced by a process of mechanical exfoliation and dry transfer.

By exploiting oxidation induced defects on the layers of black phosphorous, light tenability can be achieved, causing the layers to generate a unique persistent photo-response under the illumination of particular wavelengths of light or electromagnetic radiation. As described above, the conductance exhibited by the black phosphorous layers may increase when exposed to light with a wavelength in the range of 250 – 315 nm, and may decrease when exposed to light with a wavelength in the range of 315 – 400 nm. This effect can allow for multi-bit programming and erasing functions, image pre-processing and neuromorphic image recognition functions to be performed. According to some embodiments, while black phosphorous may exhibit an anisotropic photo-response, the above-described wavelength specific increases and decreases in conductance may be exhibited regardless of the crystal orientation of the black phosphorous.

According to some embodiments, optical sensor device 120 may further comprise a passivation layer 122, which may be a phosphorous oxide (P_xO_y) layer in some embodiments. The native phosphorous oxide layer may form on top of black phosphorous substrate 121 due to the exposure of substrate 121 with oxygen, and may act as a self-passivation layer for the black phosphorous to protect it from further corrosion. Furthermore, layer 122 may induce localised trap sites for charge carriers, causing unusual negative photoconductivity under optical excitation, allowing for the

unique band selective photo-response under different wavelengths of electromagnetic radiation as described above. According to some embodiments, passivation layer 122 may form on both the top and bottom of black phosphorous substrate 121. According to some embodiments, layer 122 may be between 1 and 5nm thick.

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Optical sensor device 120 further comprises an electrically insulating substrate 123, which may be a SiO₂/Si layer 123.

Optical sensor device 120 further comprises electrodes 124, which allow a voltage to be applied between them and to pass through layer 121. According to some embodiments, the electrodes may each comprise two layers, such as a chromium layer and a gold layer, for example.

Layers 121, 122 and 123, and electrodes 124 may be positioned on a back gate 125. Back gate 125 may be configured to act as a third electrode, and may allow optical sensor device 120 to perform gate-assisted write and erase functions, as described in further detail below with reference to Figures 6A and 6B.

Figure 13 shows a method of capturing image data using image capture device 110.

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At step 1310, processor 140 executing exposure control module 153 is caused to control exposure control device 130 in order to cause exposure control device 130 to adopt a exposure mode, in which exposure control device 130 causes optical sensor device 120 to be exposed to first electromagnetic radiation. Where exposure control device 130 comprises a shutter or filter, adopting the exposure mode may comprise opening the shutter or filter. Where exposure control device 130 comprises a source of electromagnetic radiation such as a light 132, adopting the exposure mode may comprise switching on the source of electromagnetic radiation. The electromagnetic radiation may be of a first predetermined wavelength, which may cause an increase in conductance of optical sensor device 120 or otherwise cause data to be written to optical sensor device 120.

At step 1320, processor 140 executing exposure control module 153 is caused to control exposure control device 130 in order to cause exposure control device 130 to adopt a protected mode, in which optical sensor device 120 is blocked from or otherwise no longer exposed to the first electromagnetic radiation. According to some

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embodiments, processor 140 may execute step 1320 after a predetermined period of time has elapsed after performing step 1310. Where exposure control device 130 comprises a shutter or filter, adopting the protected mode may comprise closing the shutter or filter. Where exposure control device 130 comprises a source of
5 electromagnetic radiation such as a light 132, adopting the protected mode may comprise switching off the source of electromagnetic radiation.

At step 1330, processor 140 executing data capture module 152 is caused to read
10 reading data captured by optical sensor device 120. According to some embodiments, processor 140 may be caused to apply a voltage to optical sensor device 120 in order to determine a conductance or resistance of the optical sensor device 120 based on the applied voltage. According to some embodiments, the measured conductance or resistance may be compared with one or more predetermined threshold values to determine a value stored by optical sensor device 120.

15 At step 1340, processor 140 executing data capture module 152 may be caused to store the value read from optical sensor device to data 159 of long term memory 150.

20 In some embodiments, processor 140 may then be configured to perform steps 1350 and 1360 to erase the data from optical sensor device 120.

At step 1350, processor 140 executing exposure control module 153 is caused to control exposure control device 130 in order to cause exposure control device 130 to adopt a exposure mode, in which exposure control device 130 causes optical sensor
25 device 120 to be exposed to second electromagnetic radiation. Where exposure control device 130 comprises a shutter or filter, adopting the exposure mode may comprise opening the shutter or filter. Where exposure control device 130 comprises a source of electromagnetic radiation such as a light 132, adopting the exposure mode may comprise switching on the source of electromagnetic radiation. The electromagnetic
30 radiation may be of a second predetermined wavelength, , which may cause a decrease in conductance of optical sensor device 120 or otherwise cause data to be erased from optical sensor device 120.

At step 1360, processor 140 executing exposure control module 153 is caused to
35 control exposure control device 130 in order to cause exposure control device 130 to adopt a protected mode, in which optical sensor device 120 is blocked from or

otherwise no longer exposed to the second electromagnetic radiation. According to some embodiments, processor 140 may execute step 1320 after a predetermined period of time has elapsed after performing step 1310. Where exposure control device 130 comprises a shutter or filter, adopting the protected mode may comprise closing the shutter or filter. Where exposure control device 130 comprises a source of electromagnetic radiation such as a light 132, adopting the protected mode may comprise switching off the source of electromagnetic radiation.

Figures 3A and 3B show graphs illustrating the optical modulation and memory function of an optical sensor device 120 under two illumination wavelengths. Figure 3A relates to a scenario in which sensor device 120 was exposed to a 280nm light source such as light source 132, while Figure 3B relates to a scenario in which sensor device 120 was exposed to a 365nm light source such as light source 134. In each case, a voltage of 50 mV was applied to sensor device 120 via electrodes 124 (the drain-source voltage V_{DS}), while the voltage at back gate 125 (the gate-source voltage V_{GS}) was held at 0 V.

Turning to Figure 3A, the illustrated graph 300 has an X-axis 310 displaying time in seconds, and a Y-axis 320 displaying the normalised current I_{DS} . Bars 330 correspond to times at which sensor device 120 was exposed to the 280nm light source 132, and line 340 illustrates the current measured in sensor device 120 at each point in time, corresponding to the normalised transient photo-response of sensor device 120 to the illumination pulses illustrated by bars 330. As sensor device 120 is exposed to the light, a positive photocurrent is generated resulting in an increase in the measured current. This is due to the trapping of photo-excited charge carriers at localised trap sites induced by the surface oxidation of the sensing element 121, as described above with reference to Figure 2. When the exposure is stopped, the current gradually decreases over time, due to the release of the photo-excited charge carriers.

Turning to Figure 3B, the illustrated graph 350 has an X-axis 360 displaying time in seconds, and a Y-axis 370 displaying the normalised current I_{DS} . Bars 380 correspond to times at which sensor device 120 was exposed to the 365nm light source 134, and line 390 illustrates the current measured in sensor device 120 at each point in time, corresponding to the normalised transient photo-response of sensor device 120 to the illumination pulses illustrated by bars 380. As sensor device 120 is exposed to the light, a negative photocurrent is generated resulting in a reduction to the measured current.

This is due to the release of photo-excited charge carriers at localised trap sites induced by the surface oxidation of the sensing element 121, as described above with reference to Figure 2. When the exposure is stopped, the current gradually increases over time, due to the trapping of further photo-excited charge carriers.

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Figures 4A, 4B and 4C show graphs illustrating the dynamic memory access operation of optical sensor device 120 in an all-optical memory mode, taking advantage of the phenomenon illustrated by Figures 3A and 3B. In the all-optical memory mode, both write and erase functions can be achieved by exposing optical sensor device 120 to electromagnetic radiation in the form of optical pulses, which may be done by processor 140 controlling exposure control device 130. Read functions are performed by applying voltage pulses to electrodes 124, but no voltage is applied to gate 125.

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Turning to Figure 4A, the illustrated graph 400 has an X-axis 405 displaying time in milliseconds, and a Y-axis 410 displaying the power in mW/cm^2 of illumination supplied to optical sensor device 120 by lights 132 and 134. Bars 415 correspond to times at which sensor device 120 was exposed to the 280nm light source 132, and bars 420 correspond to times at which sensor device 120 was exposed to the 365nm light source 134.

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Figure 4B shows a graph 430 having an X-axis 435 displaying time in milliseconds, and a Y-axis 440 displaying the voltage in mV applied to electrodes 124 for the purpose of reading data from optical sensor device 120. Bars 445 correspond to times at which the voltage pulses were applied, and line 450 corresponds to the voltage applied over time, being 50mV during a read pulse and 0V between pulses.

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Figure 4C shows a graph 460 having an X-axis 465 displaying time in milliseconds, and a Y-axis 470 displaying the normalised current I_{DS} produced by optical sensor device 120. Bars 475 correspond to times at which the voltage pulses were applied. Bars 480 correspond to times at which sensor device 120 was exposed to 280nm light source 132, and bars 485 correspond to times at which sensor device 120 was exposed to 365nm light source 134. Line 490 illustrates the current measured in sensor device 120 at each point in time, corresponding to the normalised transient photo-response of sensor device 120 to the illumination pulses illustrated by bars 480 and 485. When sensor device 120 is exposed to the 280nm light, a positive photo-current is generated resulting in an increase in the measured current. When sensor device 120 is exposed to

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the 365nm light, a negative photo-current is generated resulting in a decrease in the measured current.

In reference to Figures 4A, 4B and 4C, it is shown that initially at 0 milliseconds, a
5 40ms “read” voltage pulse of 50mV is applied to quantify the “off” state of the current
of optical sensor device 120 with no exposure to light. As shown, the current is
measured to be around 0.33 μ A. To program optical sensor device 120, at 40ms optical
sensor device 120 is exposed to a “write” light pulse of 280nm with a power density of
3.5mW/cm² for 10ms, while no voltage is applied. Subsequently, another “read”
10 voltage pulse is applied to measure the now “on” state current of optical sensor device
120. As the “write” pulse has generated photo-excited carriers, the current shows an
increase, being at around 0.61 μ A. During the “read” pulse, the current slowly decays
over time.

15 The relatively slow recovery of the current after exposure to the light sources can be
attributed to the charge carrier recombination through oxidation induced in localised
trap centres within the optical sensor device 120, as described above with reference to
Figure 2. As such, optical sensor device 120 shows a persistent photo-current even after
illumination is removed, and this residue photo-current persists even after a long
20 retention time. According to some embodiments, optical sensor device 120 may retain
some photo-current for over 5.5 hours.

To reset optical sensor device 120, at 90ms optical sensor device 120 is exposed to an
“erase” light pulse of 365nm with a power density of 7.3mW/cm² for 10ms, while no
25 voltage is applied. A comparatively higher power density “erase” pulse may be used
compared to the “write” pulse to compensate for the magnitude difference in photo-
current. Subsequently, another “read” voltage pulse is applied to measure the now “off”
state current of optical sensor device 120. As the “erase” pulse has induces a negative
photo-current, the current shows a decrease to its initial “off” state of around 0.33 μ A.

30 Further “write”, “read” and “erase” actions are performed as illustrated. According to
some embodiments, optical sensor device 120 may be capable of performing at least
2000 “write” and “erase” cycles without any deterioration in cyclic endurance or
stability, indicating repeatability and reproducibility of such a device.

35

As described above, optical sensor device 120 may be able to deliver ultrafast operation speeds, as it is triggered with photonic signals. This allows sensor device 120 to be used in applications such as in-pixel image processing and facial recognition to realize efficient hardware for artificial intelligence, as described in further detail below. In contrast, previous optoelectronic memories have shown comparatively lower switching speeds (in milliseconds to seconds) than known electronic memories (which have switching speeds in the range of nanoseconds to sub-microseconds). This is because in electronic memories, fast charge injection through localized switching paths or floating gate charge storage render high switching speed. On the other hand, material dependent dynamics of photo-excited charge carries and associated mechanisms such as trapping/de-trapping can be responsible for the slow operational speeds in previous optoelectronic memories.

In contrast, optical sensor device 120 may exhibit switching speed with optical pulses of around 10ms duration, being more than two orders of magnitude higher than some previous known optoelectronic memories.

Due to the persistent photo-current, slow recovery and long retention time, optical sensor device 120 may be used for multi-bit data programming and storage. Figures 5A, 5B and 5C shows graphs illustrating optical sensor device 120 being used for writing, erasing and reading 8-bit data.

Figure 5A shows a graph 500 having an X-axis 505 displaying time in seconds, and a Y-axis 510 displaying the power in mW/cm^2 of illumination supplied to optical sensor device 120 by a light source that induces an “erase” action. For example, the illumination may be a 365nm light pulse emitted by a light source such as light source 134. Line 515 shows the power of illumination supplied to optical sensor device 120 by light 134 over time, showing a single 15 second pulse of $8.5 \text{ mW}/\text{cm}^2$ of illumination at around 460 seconds.

Figure 5B shows a graph 530 having an X-axis 535 displaying time in seconds, and a Y-axis 540 displaying the power in mW/cm^2 of illumination supplied to optical sensor device 120 by a light source that induces a “write” action. For example, the illumination may be a 280nm light pulse emitted by a light source such as light source 132. Line 545 shows the power of illumination supplied to optical sensor device 120 by

light 132 over time, showing a seven 5 second pulse of 3.5 mW/cm^2 of illumination with a period of 55 seconds.

Figure 5C shows a graph 560 having an X-axis 565 displaying time in seconds, and a
5 Y-axis 570 displaying the current in μA produced by optical sensor device 120 when exposed to the pulses of Figures 5A and 5B, as well as a voltage of 50mV applied to electrodes 124. As shown, the multiple “write” pulses cause the current generated by sensor device 120 to increase in steps, until the “erase” pulse causes the current to drop below the reference current or “off” current exhibited by sensor device 120 when it is
10 not exposed to any light sources. The current then recovers back to the reference or “off” current after termination of the “erase” pulse. This demonstrates optical sensor device 120 being able to adopt at least eight different memory states, which can be programmed and erased electronically. This allows optical memory device 120 to be used for optoelectronic in-memory computation and logic operations such as image
15 processing and neuromorphic computation, as described in further detail below.

As well as being able to store and erase data purely optically, optical sensor device 120 may further be able to be used in a gate-assisted mode, where voltage can be applied to back gate 125 to perform further processing functions. In this case, optical sensor
20 device 120 may operate in a three-terminal field effect transistor configuration, where illumination applied to optical sensor device 120 may be used to modulate the transfer characteristics.

Figures 6A and 6B show example transfer characteristics of optical sensor device 120
25 acting in an optical mode, and a gate-assisted mode.

Figure 6A shows a graph 600 showing example transfer characteristics of optical sensor device 120 acting in an optical-only mode, in which the voltage V_{GS} at back gate 125 is 0V. X-axis 610 shows the voltage V_{DS} applied to electrodes 124 in volts, while
30 Y-axis 620 shows the output drain-source current profiles I_{DS} exhibited by optical sensor device 120 in μA . Reference line 630 shows the current produced when optical sensor device 120 is not exposed to any illumination.

Lines 632 show the current produced by optical sensor device 120 under different
35 power densities of 280nm illumination. As shown in graph 600, under 280nm illumination, I_{DS} increases with respect to reference line 630 as the power density

increases. Lines 634 show the current produced by optical sensor device 120 under different power densities of 365nm illumination. As shown in graph 600, under 365nm illumination I_{DS} decreases proportionally with respect to reference line 630 as the power density increases.

5

Figure 6B shows a graph 650 showing example transfer characteristics of optical sensor device 120 acting in a gate-assisted mode, in which the voltage V_{GS} at back gate 125 is varied. X-axis 660 shows the gate voltage V_{GS} applied to back gate 125, while Y-axis 670 shows the output drain-source current profiles I_{DS} exhibited by optical sensor device 120 in μA . Reference line 680 shows the current produced when optical sensor device 120 is not exposed to any illumination.

10

Lines 682 show the current produced by optical sensor device 120 under different power densities of 280nm illumination. Lines 684 show the current produced by optical sensor device 120 under different power densities of 365nm illumination. The calculated carrier mobility increases and decreases after illumination with 280nm and 365nm wavelengths, respectively, compared to reference line 680. This increase in mobility under 280nm illumination may be associated with the high energy of hot carriers gained under high energy excitation, while the mobility decreases under 365nm illumination may be due to the carrier scattering by charged defects under low energy excitation, as described in further detail below. As such, the change in conductance of optical sensor device 120 regulated by optical signals under the influence of voltage applied to back gate 125 allows for programming and erasing capabilities by simply applying specified wavelengths, such as 280 nm and 365 nm wavelengths, respectively

25

The transfer characteristics of optical sensor device 120 in gate-assisted mode demonstrate the power-dependent multi-level data programming and erasing operations that can be achieved with optical sensor device 120.

30

Further observing Figure 6B, it can be clearly observed that the threshold voltages V_{TH} of the transfer curves shifts during gate-assisted “write” and “erase” operations. This V_{TH} shift is possibly due to the electrostatic screening by light induced charge trapping at the surface of layers 121 and 122 of or bottom of the layer 121/122/123 interface. As shown in graph 650, during the “write” operation, V_{TH} steadily increases from +3.45 V to +27.35 V when the illumination power density of the 280 nm illumination pulses increases from 0.5 mW/cm² to 3 mW/cm². During the “erase” operation, V_{TH} shifts

35

from -4.8 V to -11.59 V as the power density of the 365 nm illumination pulses increase from 2 mW/cm² to 10 mW/cm². As such, in the gate-assisted configuration, a memory window is defined by the difference between the programming or “write” state V_{TH} and the “erase” state V_{TH} . A maximum memory window of ~38.94 V may be
5 observed for power densities of 3 mW/cm² and 10 mW/cm² during “write” and “erase” operations, for example.

According to some embodiments, optical sensor device 120 may show good endurance and cyclic repeatability of the optical “write” and “erase” operations in gate-assisted
10 mode. For example, in some embodiments, optical sensor device 120 may exhibit no significant degradation in the memory window after more than 500 consecutive “write” and “erase” cycles in ambient conditions.

The described features, characteristics and properties of optical sensor device 120,
15 image capture device 110 and system 100 may allow them to be configured to perform image processing functions such as image detection and memorisation. Specifically, the deep trap-states assisted slow recovery and persistent photo-current exhibited by optical sensor device 120 allows for on-chip image-processing functions such as weak signal accumulation for real-time image enhancement. Furthermore, in-pixel storage can be
20 used to achieve massive parallel computation.

According to some human memory models, external information received by human sensory organs is stored as a sensory memory for a very short time and then selected information is transferred from a temporary short-term memory (STM) to a permanent
25 long-term memory (LTM). The STM corresponds to temporally weak neural plasticity which persists for a short duration, ranging from a few seconds to minutes. However, via the process of consolidation which involves repetitive stimuli and frequent rehearsals, the STM transforms into LTM, which corresponds to a temporally stronger neural plasticity lasting from several minutes to years. Using optical pulses as stimuli
30 for optical sensor device 120 and varying their frequency by controlling exposure control device 130, these human memory behaviours including a transition of STM to LTM and optically tunable synaptic plasticity can be imitated by image capture device 110.

35 Figures 7A and 7B show examples of optical sensor device 120 exhibiting STM and LTM.

Figure 7A shows a diagram 700 in which an optical sensor device 120 is caused to exhibit STM. The illustrated optical sensor device 120 is a 2x2 pixel chip, comprising four pixels I, II, III and IV. Each pixel comprises layers 121, 122 and 123 as well as electrodes 124, all sharing a single back gate 125. Exposure control device 130, which may be two light sources 132 in some embodiments, is caused to illuminate two pixels with a series of “write” illumination pulses, which may be 280nm pulses in some embodiments. In the illustrated embodiment, pixels II and IV are illuminated with 100 consecutive short optical pulses with pulse width of 50 ms and a power density of 3 mW/cm² at 1 Hz.

Images 720, 730 and 740 shows the current of each pixel 710 measured at various times. For comparison, the current of each pixel is scaled between 0 and 1 as shown in key 701, with 0 corresponding to the minimum measured current, being around 0.95 μ A, and 1 corresponding to the maximum measured current, being around 3.93 μ A.

Image 720 shows the current of each pixel 710 measured before the illumination pulses are delivered. The current of each pixel 710 is relatively low

Image 730 shows the current of each pixel 710 measured within 0.5 seconds of the illumination pulses being delivered. Pixels II and IV show a relatively high current compares to pixels I and III, corresponding to the illumination pulses they have received.

Image 740 shows the current of each pixel 710 measured 10 minutes after the illumination pulses delivered. The current of each pixel 710 has returned to a similar level as that exhibited by pixels 710 before receiving the illumination pulses. This corresponds to a STM effect.

Figure 7B shows a diagram 750 in which an optical sensor device 120 is caused to exhibit LTM. The illustrated optical sensor device 120 is the same 2x2 pixel chip shown in Figure 7A. Exposure control device 130, which may be two light sources 132 in some embodiments, is caused to illuminate two pixels with a series of “write” illumination pulses, which may be 280nm pulses in some embodiments. In the illustrated embodiment, pixels I and III are illuminated with 100 consecutive short

optical pulses with pulse width of 50 ms and a power density of 3 mW/cm², this time at 10 Hz.

Images 770, 780 and 790 shows the current of each pixel 710 measured at various
5 times. For comparison, the current of each pixel is scaled between 0 and 1 as shown in
key 701, being the same scale used in Figure 7A.

Image 770 shows the current of each pixel 710 measured before the illumination pulses
are delivered, and after an erase has been performed. The current of each pixel 710 is
10 relatively low.

Image 780 shows the current of each pixel 710 measured within 0.5 seconds of the
illumination pulses being delivered. Pixels I and III show a relatively high current
compares to pixels II and IV, corresponding to the illumination pulses they have
15 received. The difference in current is even greater than that exhibited by the pixels as
shown in image 730 of Figure 7A.

Image 790 shows the current of each pixel 710 measured 10 minutes after the
illumination pulses delivered. In this case, while the current of each pixel 710 has
20 started returning to a similar level as that exhibited by pixels 710 before receiving the
illumination pulses, the difference between the illuminated pixels I and III and the
unilluminated pixels II and IV is still measurable. This corresponds to a LTM effect.
The increase in conductance contrast within optical sensor device 120 at higher
illumination frequencies highlights the capability of using image capture device 110 for
25 in-pixel image enhancement and real-time data processing of the input visual
information.

The described features, characteristics and properties of optical sensor device 120,
image capture device 110 and system 100 may further allow them to be configured to
30 perform machine learning functions. For example, Figure 8 shows a method of training
image capture device 110 to act as an optical neural network to perform handwriting
recognition. In the illustrated embodiments, optical sensor device 120 acts as a neural
network comprising an input layer 820, a weight matrix 830 and an output layer 840. In
the illustrated embodiments, input layer 820 comprises 28x28 input neurons numbered
35 X₀ to X₇₈₃, and output layer 840 comprises 10 output neurons numbered Y₀ to Y₉. Each
input neuron may comprise a pixel 710. The input neurons are connected to the output

neurons through weight matrix 830, which in the illustrated embodiment comprises 784x10 synaptic weights, with each input neuron being connected to each output neuron through an individual synaptic weight. Each synaptic weight is the conductance of the pixel 710, and depends on intensity or dosage of the light exposed onto the pixel
 5 710.

Optical sensor device 120 is trained via a single-layer perceptron model performing supervised learning with a back-propagation algorithm, using a plurality of training images. For example, Figure 8 shows an example 28x28 pixel input image 810, being a
 10 handwritten “0” digit. Each training image may be associated with a label value k_n . For example, the label k_n associated with input image 810 may be the value “0”. The input images may be obtained from a database such as the Modified National Institute of Standards and Technology (MNIST) dataset. According to some embodiments, between 10,000 and 100,000 training images may be used.

15 During training, each neuron in the input layer 820 receives stimulation corresponding to a pixel in the image 810 and is assigned to an input vector X_m . Input vector X_m is then transformed to 10 output values Σ_n of output layer 840 through weight matrix 830 ($W_{m,n}$) to feed the output neurons Y_0 to Y_9 . The values of Σ_n are converted to an output
 20 vector Y_n by a sigmoid activation function. For example, output vector Y_n may be determined by calculating:

$$Y_n = f(\Sigma_n) = \frac{1}{1 + e^{-\Sigma_n}}$$

25 Next, the difference between the values of the output vector Y_n and the label value k_n associated with the input image is used to update the synaptic weights of weight matrix 830 through a weight update method based on the backpropagation algorithm. Specifically, the sign of the weight change $sgn(\Delta W)$ is calculated using the difference between the output value Y_n and each label value k_n to determine whether the synaptic
 30 weight needs to increase or decrease, such that:

$$\begin{aligned} sgn(\Delta W) &> 0 \text{ if } k_n - Y_n > 0 \\ sgn(\Delta W) &< 0 \text{ if } k_n - Y_n < 0 \end{aligned}$$

35 Where $sgn(\Delta W) > 0$, both the synaptic weight W and the device conductance G are increased. Conductance G refers to the real conductance value of optical sensor device

120, while synaptic weight W refers to the conductance value calculated by the neural network during recognition. Where $\text{sgn}(\Delta W) < 0$, both the synaptic weight W and the device conductance G are decreased.

- 5 During training, the calculation of synaptic weight includes both positive and negative values, while the conductance of optical sensor device 120 is always positive. To overcome this discrepancy, the synaptic weight W may be considered to be the difference of two conductance values, being $G_{m,n}$ and G_{int} , where $G_{int} = (G_{max} + G_{min})/2$. G_{max} and G_{min} may be calculated based on experimental data. According to some
10 embodiments, only $G_{m,n}$ may be used to modify the synaptic weights W of the network, while G_{int} may be used purely as a scaling factor for normalisation.

Once optical sensor device 120 is trained using the method described above, it can be used to label input images that were not part of the training dataset.

- 15 In one example, an optical sensor device 120 was trained using 60,000 images from the MNIST dataset. Sensor device 120 was then asked to label 10,000 test images which were not provided during network training, and the recognition accuracy was determined. Figures 9A and 9B shows mapping images of a representative input
20 handwritten digit '0' before and after 25,000 training phases. Figure 9A shows a heat map 900 showing the classification accuracy in an initial state before training, while Figure 9B shows a heat map 950 showing classification accuracy in a final state after training. Key 901 shows how the areas of the heat maps correspond to classification accuracy as a percentage between 0% and 100%.

- 25 The recognition accuracy was calculated for different pulse widths (1, 20, 50, 100 and 300 ms) of optical stimuli applied to optical sensor device 120, and a maximum recognition accuracy of ~90% was achieved.

- 30 A similar process can be used to train image capture device 110 to act as an optical neural network to perform face recognition, as shown in Figure 10. In the illustrated embodiments, optical sensor device 120 acts as a neural network comprising an input layer 1020, a weight matrix 1030 and an output layer 1040. In the illustrated
35 embodiments, input layer 1020 comprises 60x60 input neurons numbered I_0 to I_{3599} , and output layer 1040 comprises a single output neuron Z_{out} . The input neurons are connected to the output neurons through weight matrix 1030, which in the illustrated

embodiment comprises 3600x1 synaptic weights, with each input neuron being connected to the output neuron through an individual synaptic weight.

5 Optical sensor device 120 is trained via a single-layer perceptron model performing supervised learning with a back-propagation algorithm, using a plurality of training images. For example, Figure 10 shows an example 60x60 greyscale pixel input image 1010 of a face.

10 During training, the weight matrix 1030 is updated based on the experimental conductance modification of optical sensor device 120 depending on whether an increase or decrease in the synaptic weight is required, as described above with reference to Figure 8. The highest and lowest synaptic weights correspond to white and black pixels of the grayscale input image. In each learning epoch, 150 pixels are randomly selected to update the synaptic weight.

15 Figure 11 shows a series of images 1100 showing the evolution of the image during the learning process at various stages. As depicted by Figure 11, when optical sensor device 120 is trained with stimulation pulses of 20 milliseconds, sensor device 120 exhibits a relatively slower learning rate but a higher accuracy, as the facial details in the output image after 800 epochs are better at the final state than in the other datasets. 20 In contrast, training with the highest nonlinearity dataset using 300 millisecond pulses gives a faster learning rate, as the facial contour appear after relatively lesser training epochs, but gives the lowest accuracy with a less clear image at the final state. Using a Structural Similarity method to measure the difference between the learnt image and the input image, it was found that the final recognition accuracy of a minimal 25 nonlinearity system is higher, at around 96% in 837 epochs for 1 millisecond pulses, than that of maximum nonlinearity system, which gave an accuracy of only 53.67% in 204 epochs for 300 millisecond pulses. This result can be associated with the higher rate of weight change in a nonlinearity system and the almost even distribution of synaptic weights in a minimal nonlinearity system. These results show that the inherent 30 optical information detection, in-pixel processing and retention characteristics of the optical sensor device 120 make it possible to configure sensor device 120 to successfully imitate human visual memory.

Figure 1200 shows a flowchart illustrating a method 1200 of training optical sensor device 120 to act as a neural network for performing image recognition. Method 1200 may be performed by processor 140 executing program code 130.

- 5 At step 1210, processor 140 executing handwriting recognition module 154 or facial recognition module 155 receives training data from remote device 180 via communications module 170. The training data may comprise training images or handwritten text, faces, or other images.
- 10 At step 1220, processor 140 executes exposure control module 153 to cause exposure control device 130 to expose optical sensor device 120 to a first image from the received training data for a predetermined period of time. This may be by causing one or more light sources corresponding to pixels of the image to illuminate one or more pixels 710 of optical sensor device 120.
- 15 At step 1230, processor 140 executing handwriting recognition module 154 or facial recognition module 155 determines an output value by applying a weight matrix stored in memory 150 to the output exhibited by sensor device 120 in response to the test image.
- 20 At step 1240, processor 140 executing handwriting recognition module 154 or facial recognition module 155 compares the output value with a label associated with the test image being processed.
- 25 At step 1250, processor 140 adjusts the weight matrix stored in memory 150 based on the outcome of the comparison performed at step 1240.
- 30 At step 1260, processor 140 determines whether further training is required. This may be by comparing the number of times that optical sensor device 120 has been exposed to the current test image, and by comparing the number of test images already used with the total number of training images available.
- 35 If processor 140 determines that further training is required, then at step 1270 processor 140 executes exposure control module 153 to again cause exposure control device 130 to expose optical sensor device 120 to an image for a predetermined period of time.

The image may be the same as that already exposed to optical sensor device, or may be a new image. Processor 140 then proceeds to perform the method from step 1230.

5 If processor 140 determines that no further training is required, then at step 1280 processor 140 stores the final weight matrix 1280 in memory 150. This can then be used to process future images for the purposes of image recognition.

10 It will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the above-described embodiments, without departing from the broad general scope of the present disclosure. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive.

CLAIMS:

1. An imaging device for capturing image data, the imaging device comprising:
an optical sensor responsive to electromagnetic radiation, wherein the sensor exhibits a photo-memory effect causing the sensor to act as a short-term memory
5 device;
an exposure control device configured to adopt a first mode and a second mode, wherein in the first mode the exposure control device causes electromagnetic radiation to reach the sensor and in the second mode the exposure control device restricts electromagnetic radiation from reaching the sensor;
10 a processor configured to receive sensor data from the sensor, and to cause the exposure control device to selectively adopt the first mode and the second mode; and
a long term memory device accessible to the processor, wherein the processor is configured to read executable instructions from the long term memory and
15 to write sensor data to the long term memory;
wherein data stored in the sensor acting as a short-term memory device is erasable by exposing the photo-sensor to electromagnetic radiation.
2. The device of claim 1, wherein the optical sensor is responsive to one or more of
20 ultraviolet light, visible light, and infrared light.
3. The device of claim 1 or claim 2, wherein the optical sensor comprises a two-dimensional semiconductor.
- 25 4. The device of claim 3, wherein the two-dimensional semiconductor comprises at least one of an elemental material, transitional metal oxide, or transition metal chalcogenide.
5. The device of claim 4, wherein the two-dimensional semiconductor comprises
30 black phosphorous.
6. The device of any one of claims 1 to 5, wherein the optical sensor comprises an array of optical sensor devices.
- 35 7. The device of any one of claims 1 to 6, wherein the sensor device is configured to exhibit a reference conductance in the absence of electromagnetic radiation, and to

exhibit a wavelength dependent increase and/or decrease in conductance when exposed to electromagnetic radiation.

8. The device of claim 7, wherein the conductance of the sensor device is
5 configured to return to the reference conductance not less than 1 second after exposure to the electromagnetic radiation has ceased.

9. The device of claim 8, wherein the conductance of the sensor device is
10 configured to return to the reference conductance not less than 1 minute after exposure to the electromagnetic radiation has ceased.

10. The device of any one of claims 7 to 9, wherein the conductance of the sensor
device increases when the sensor device is exposed to electromagnetic radiation of a
first wavelength, and decreases when the sensor device is exposed to electromagnetic
15 radiation of a second wavelength.

11. The device of claim 10, wherein the first wavelength is between 250 and 315
nm, and the second wavelength is between 315 and 400 nm.

20 12. The device of any one of claims 7 to 11, wherein the processor is configured to read data stored on the sensor device by applying a voltage to the sensor device.

13. The device to any one of claims 1 to 12, wherein the exposure control device
comprises at least one of a shutter configured to block electromagnetic radiation or a
25 filter configured to filter out at least some wavelengths of electromagnetic radiation.

14. The device to any one of claims 1 to 13, wherein the exposure control device
comprises at least one source of electromagnetic radiation.

30 15. A method of capturing image data, the method comprising:
operating an exposure control device to adopt a first mode, wherein in the
first mode the exposure control device causes an optical sensor responsive to
electromagnetic radiation to be exposed to first electromagnetic radiation, wherein the
sensor exhibits a photo-memory effect causing the sensor to act as a short-term memory
35 device;

upon determining that a threshold period of time has elapsed, operating the exposure control device to adopt a second mode, wherein in the second mode the exposure control device causes the sensor to be blocked from electromagnetic radiation;

- 5 reading data captured by the sensor based on the exposure; and
 recording the read data to a long term memory device.

16. The method of claim 15, wherein the method is performed by the device of any one of claims 1 to 14.

10

17. The method of claim 15 or claim 16, further comprising erasing the read data from the sensor acting as a short term memory device by operating the exposure control device to adopt a third mode, wherein in the third mode the exposure control device causes the sensor to be exposed to second electromagnetic radiation.

15

18. The method of any one of claims 15 to 17, wherein the exposure control device comprises a shutter or filter, wherein adopting a first mode comprises opening the shutter or filter, and wherein adopting the second mode comprises closing the shutter or filter.

20

19. The method of any one of claims 15 to 18, wherein the exposure control device comprises a source of electromagnetic radiation, wherein adopting a first mode comprises switching on the source of electromagnetic radiation, and wherein adopting the second mode comprises switching off the source of electromagnetic radiation.

25

20. The method of any one of claims 15 to 19, wherein reading data captured by the sensor comprises applying a voltage to the sensor.

21. A method of training a neural network, the method comprising:

- 30 receiving at least one training image and a label related to the at least one training image;

 capturing image data by performing the method of any one of claims 15 to 20, wherein the first electromagnetic radiation is generated based on the at least one training image; and

- 35 determining an output based on the read data and a weight matrix;
 comparing the read data with the label; and

modifying the weight matrix based on the comparison.

22. The method of claim 21, further comprising repeating the method with the same at least one training image.

5

23. The method of claim 21 or claim 22, further comprising repeating the method with a further training image different to the at least one training image.

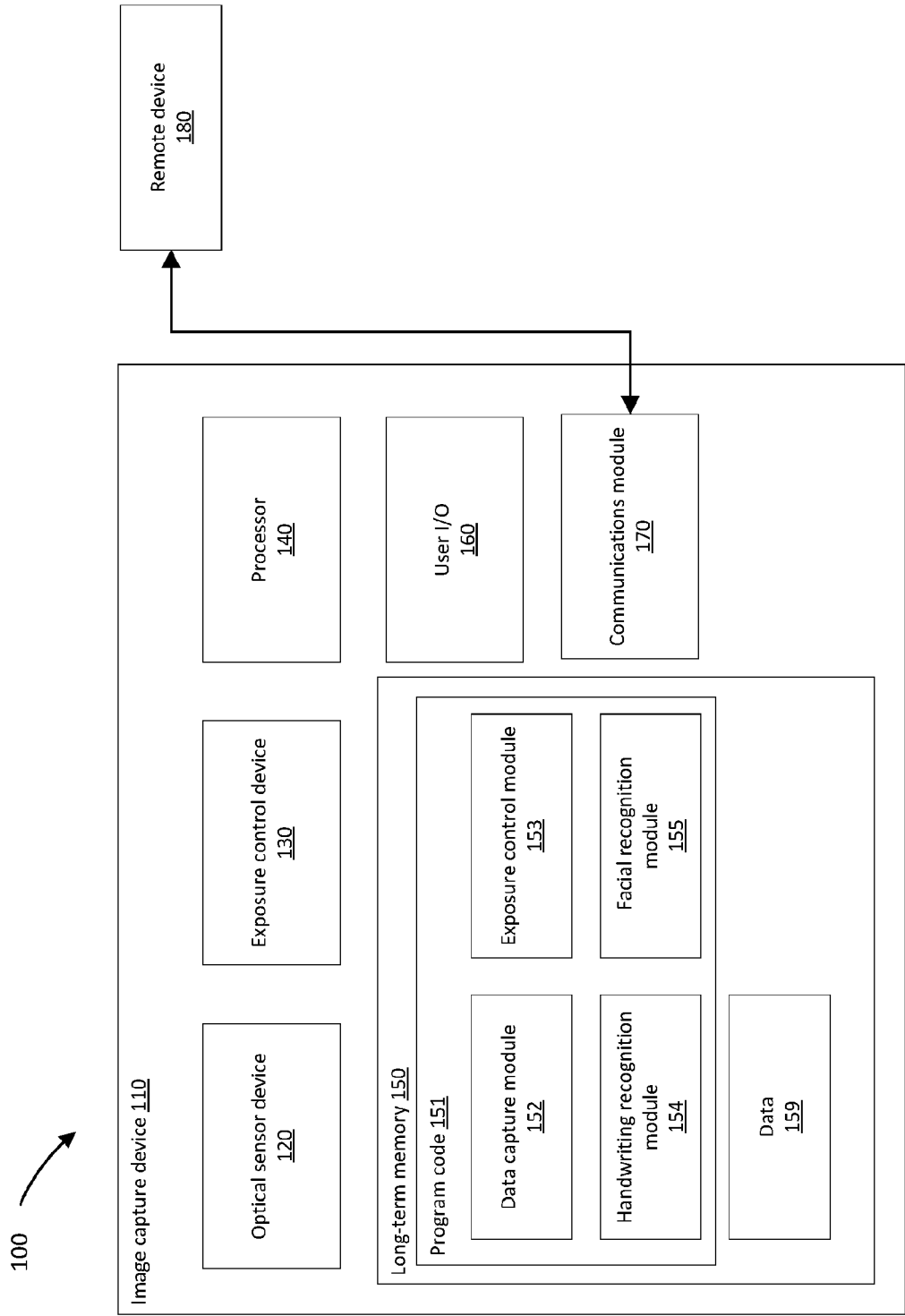


Figure 1

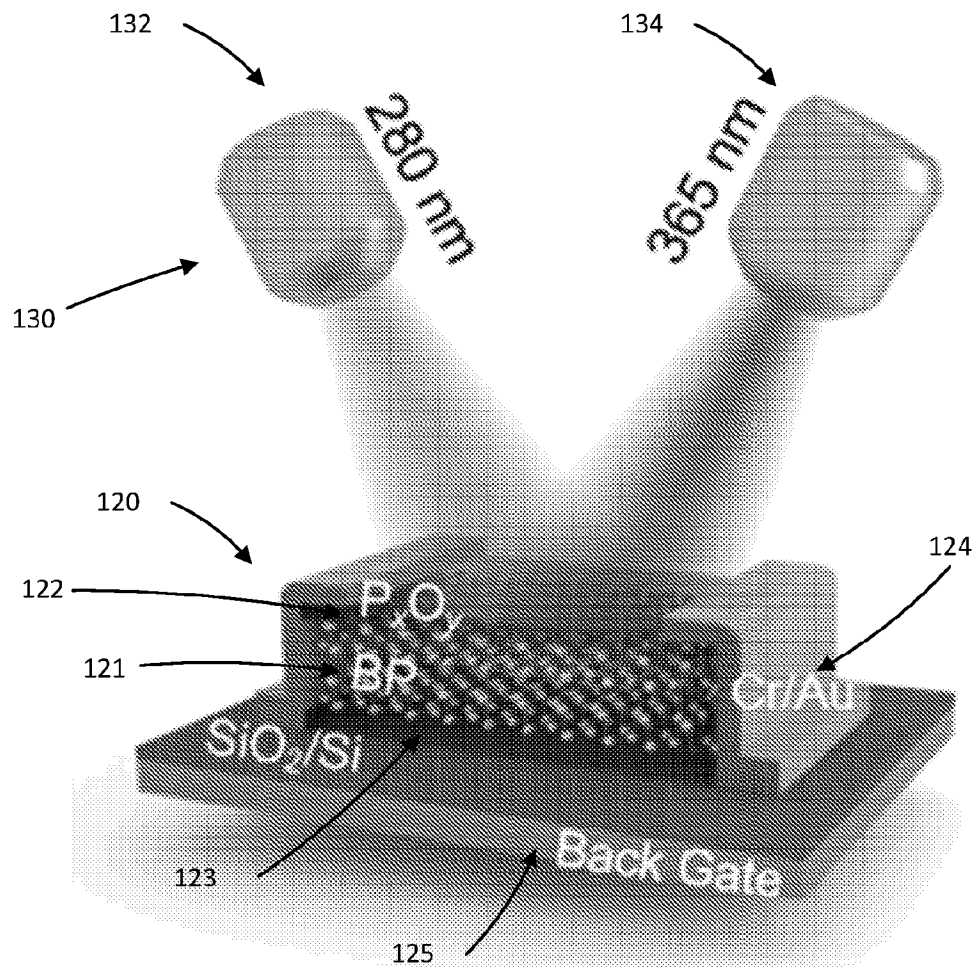


Figure 2

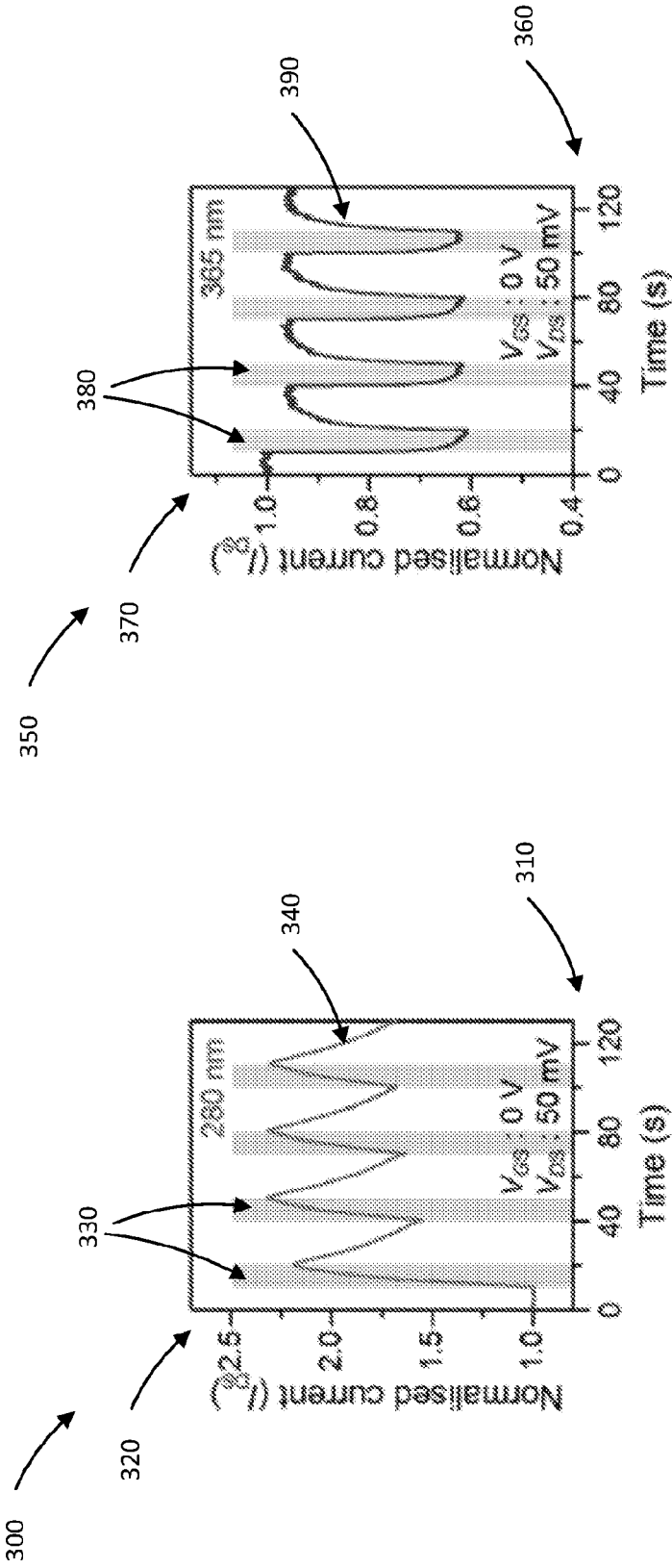


Figure 3A

Figure 3B

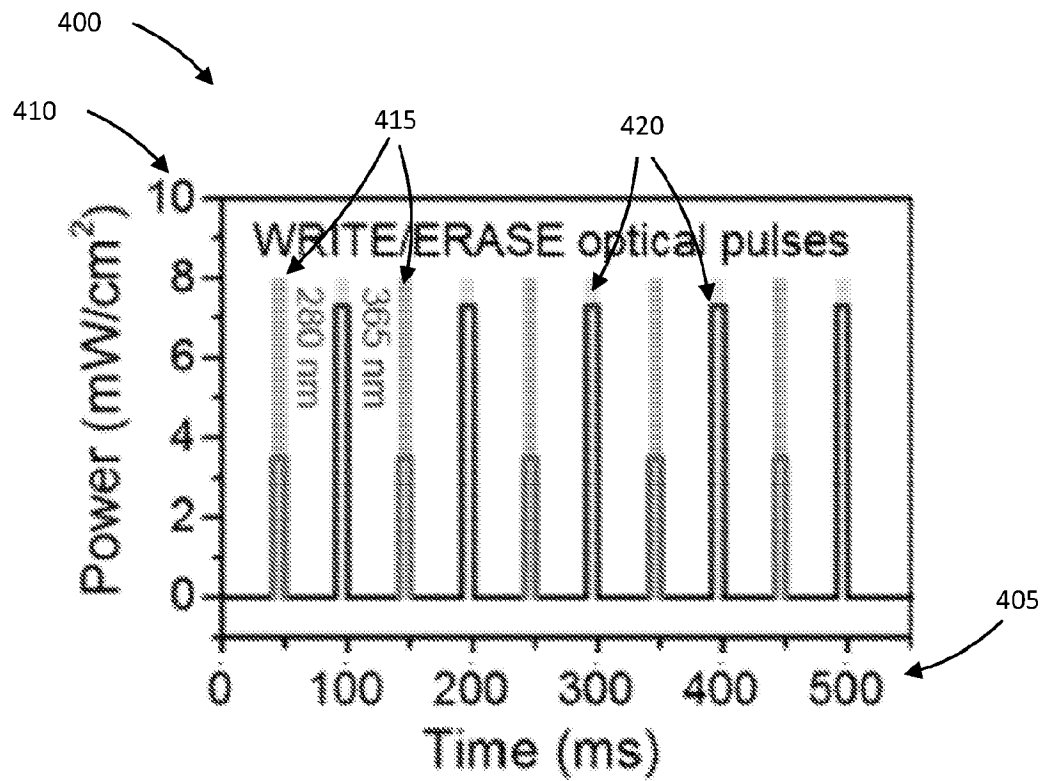


Figure 4A

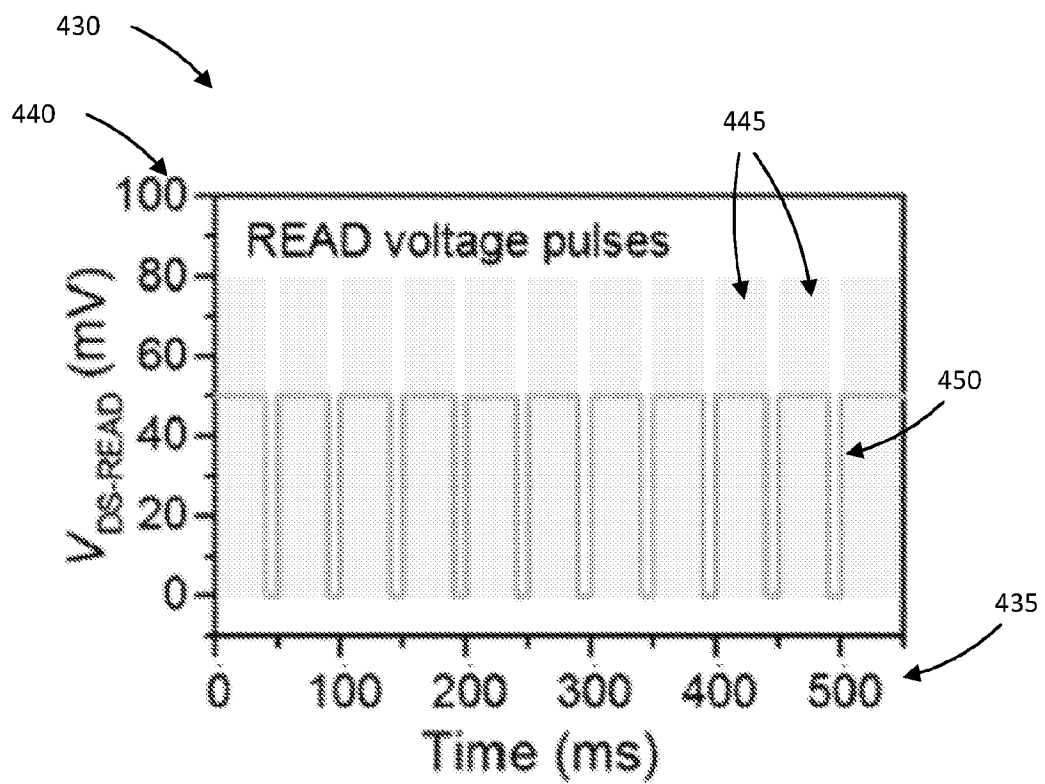


Figure 4B

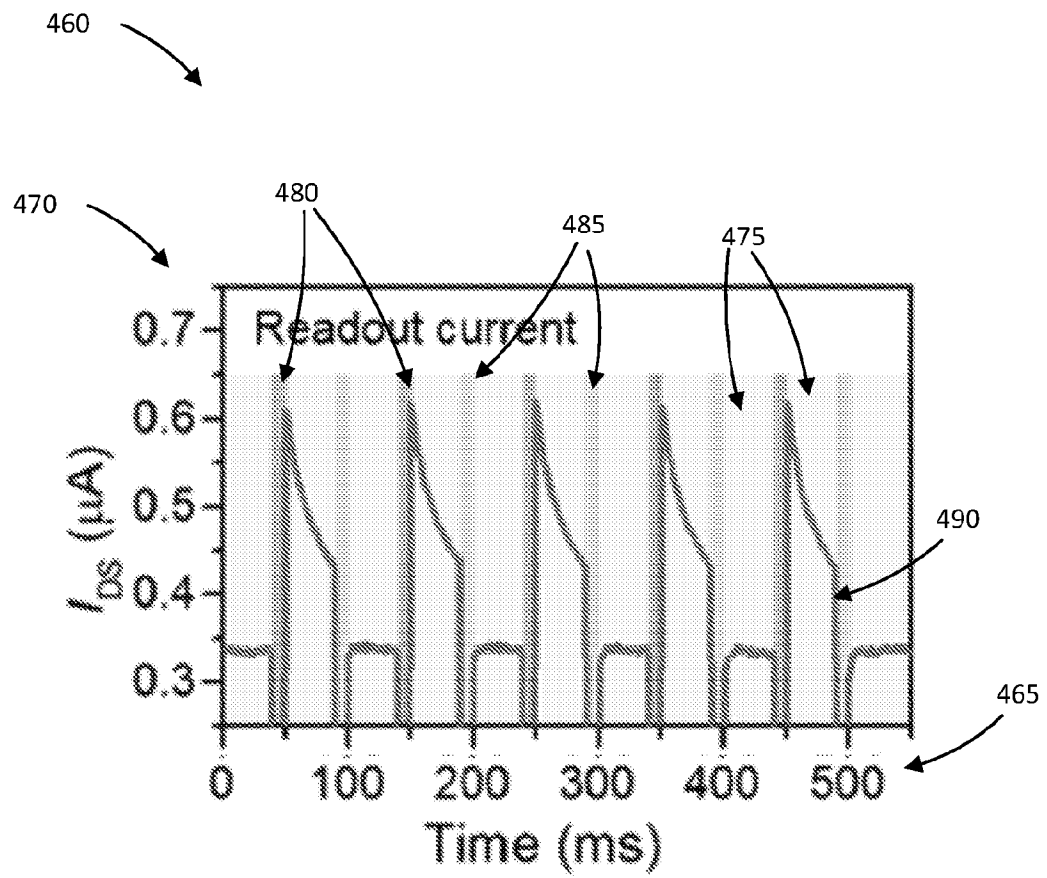


Figure 4C

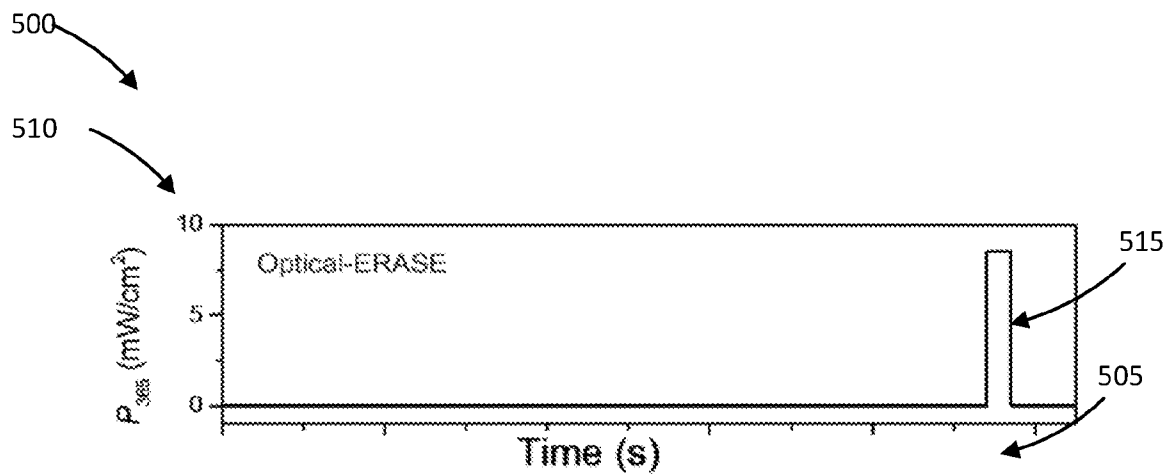


Figure 5A

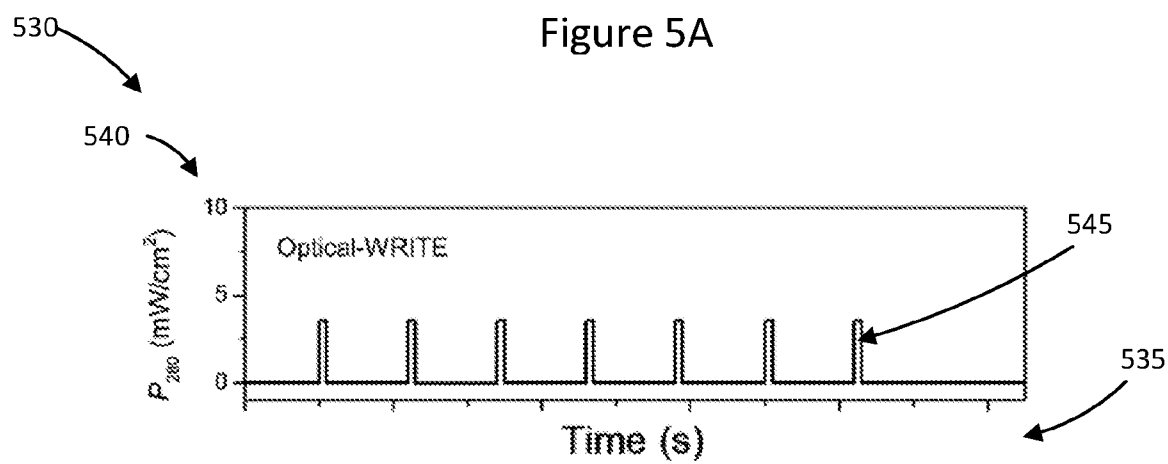


Figure 5B

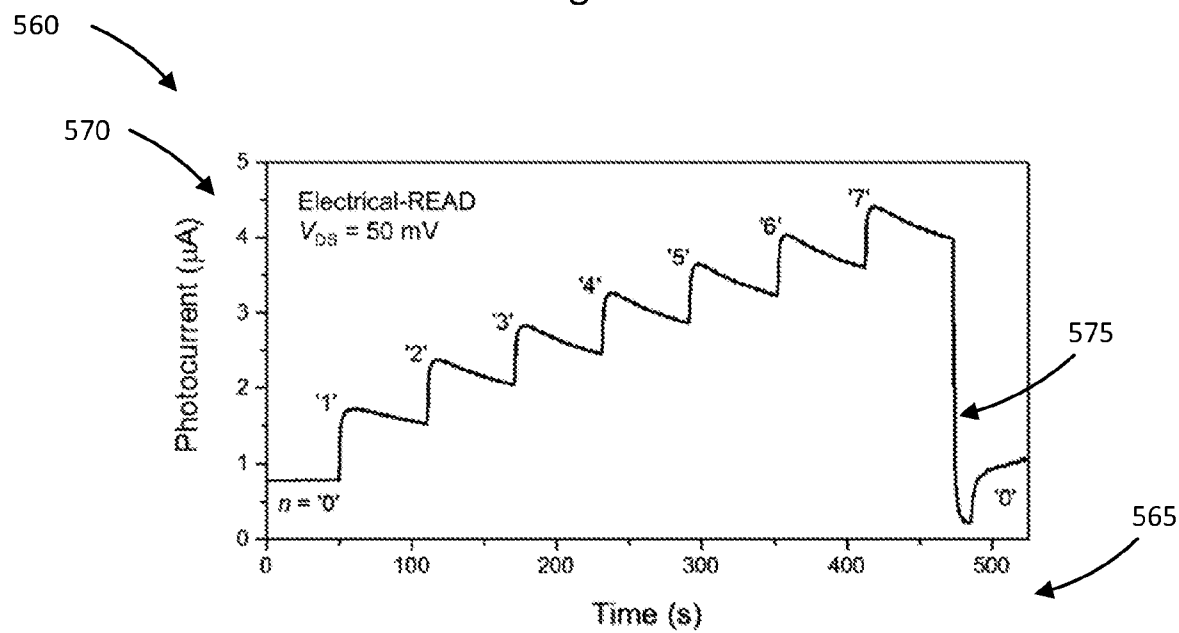


Figure 5C

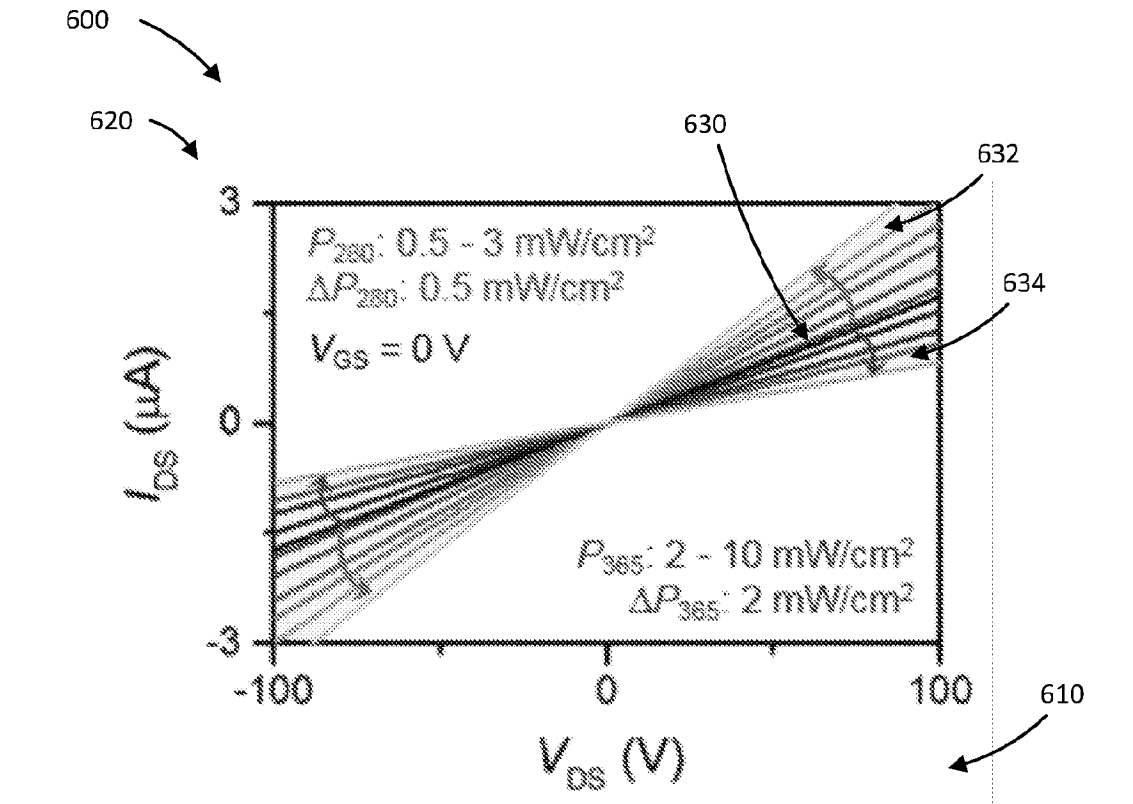


Figure 6A

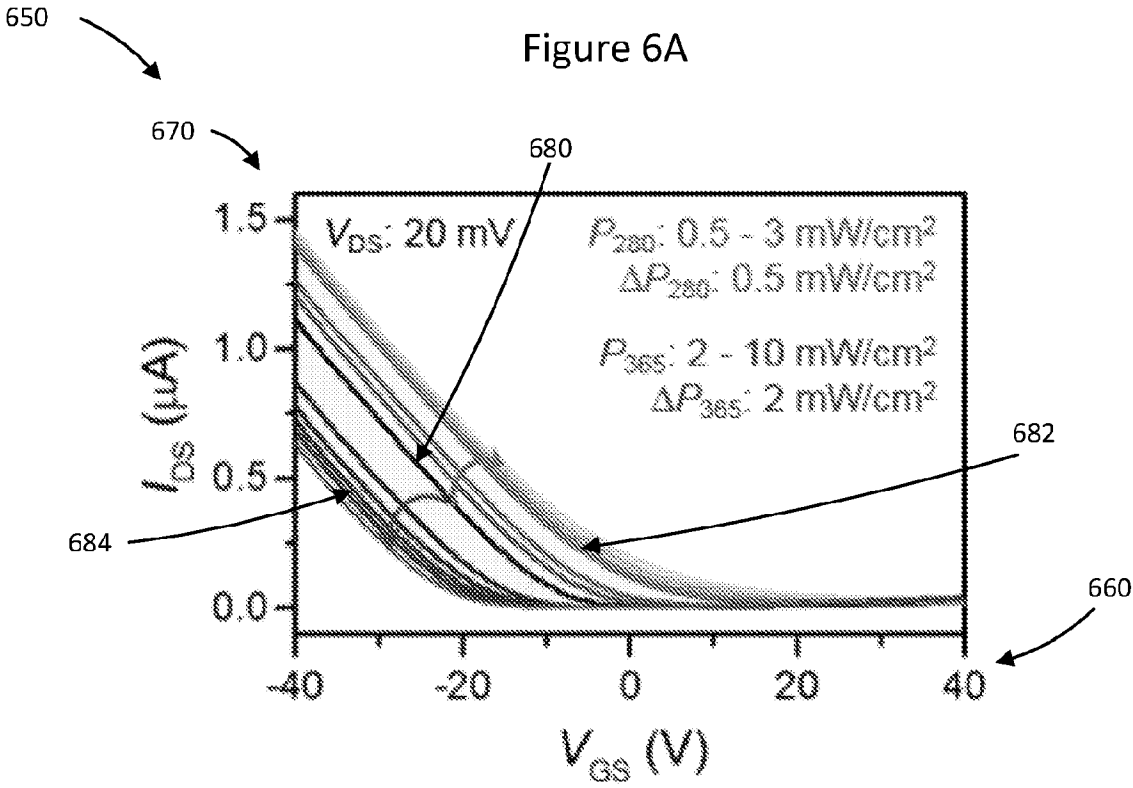


Figure 6B

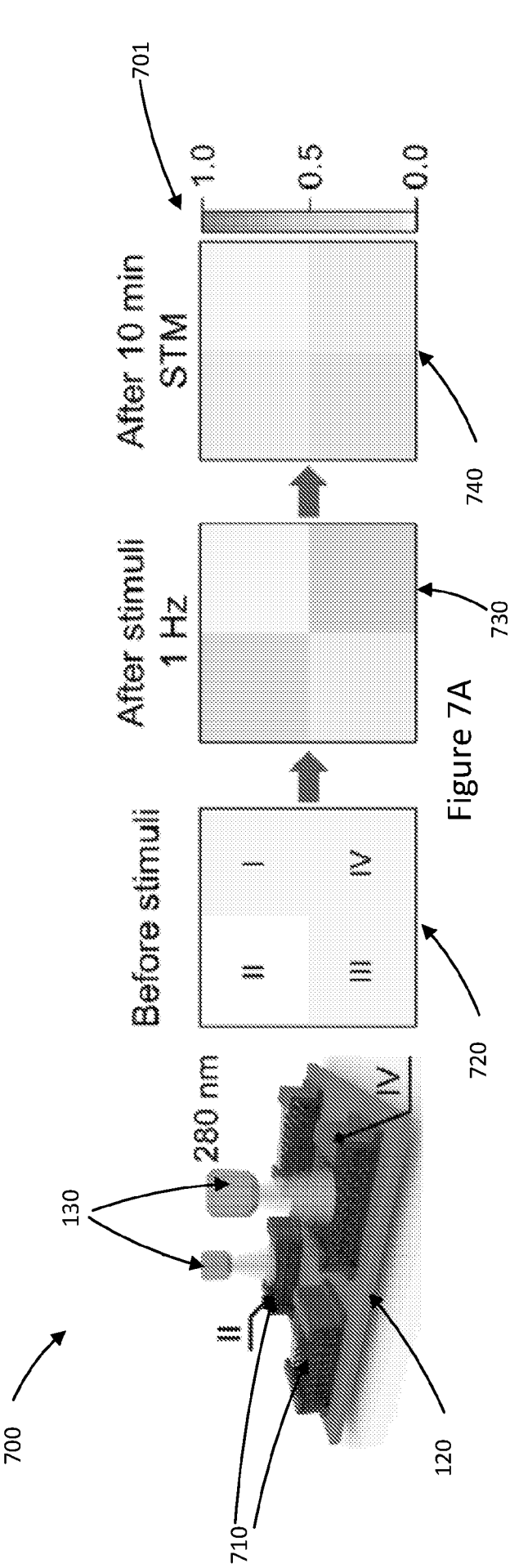


Figure 7A

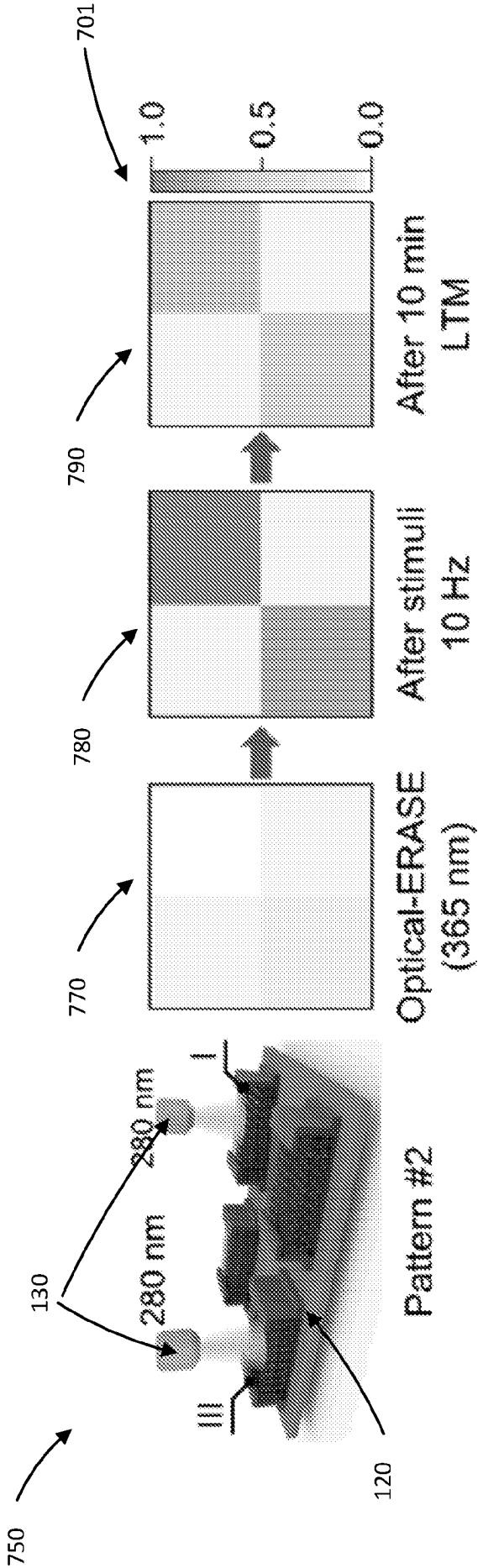


Figure 7B

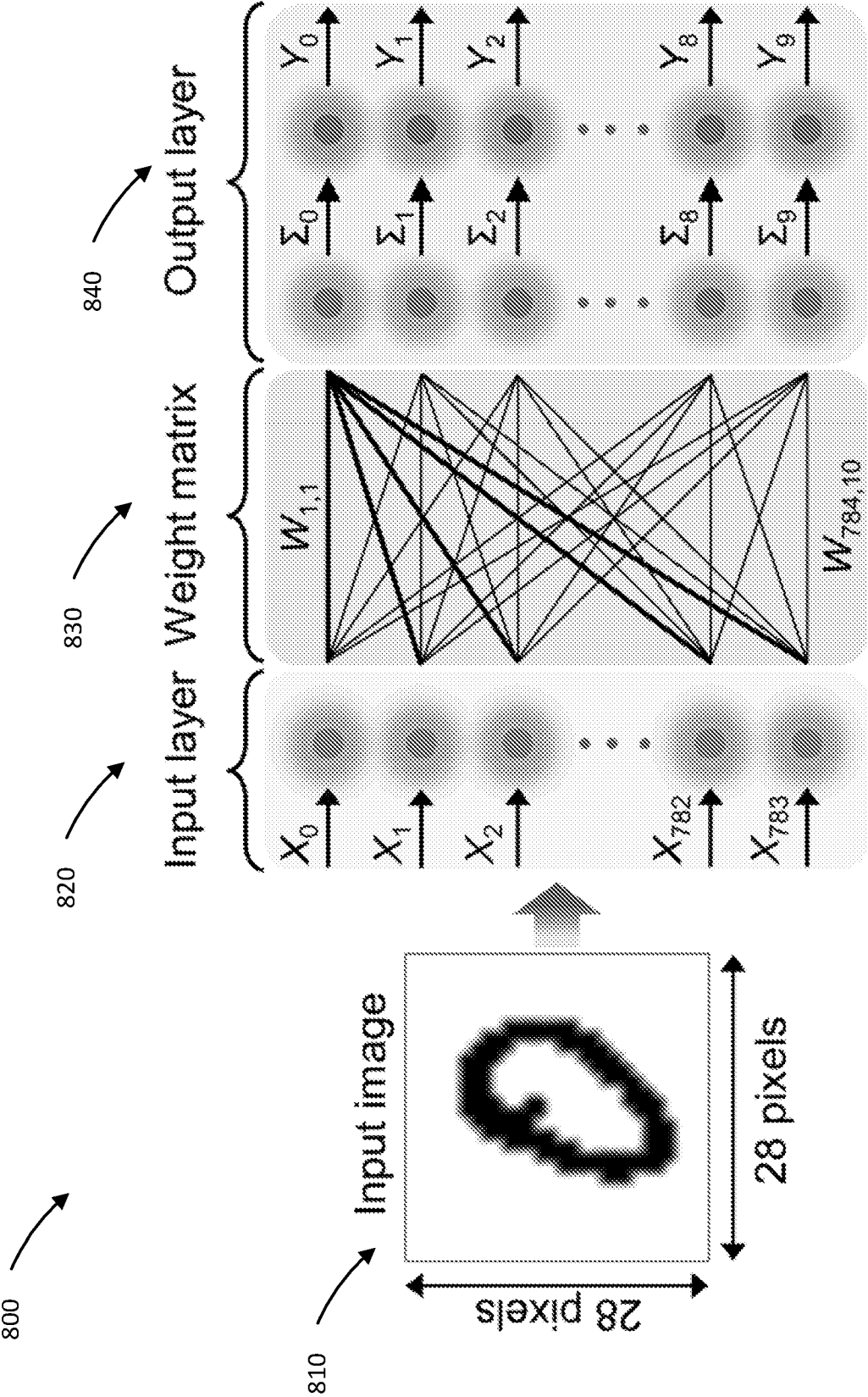
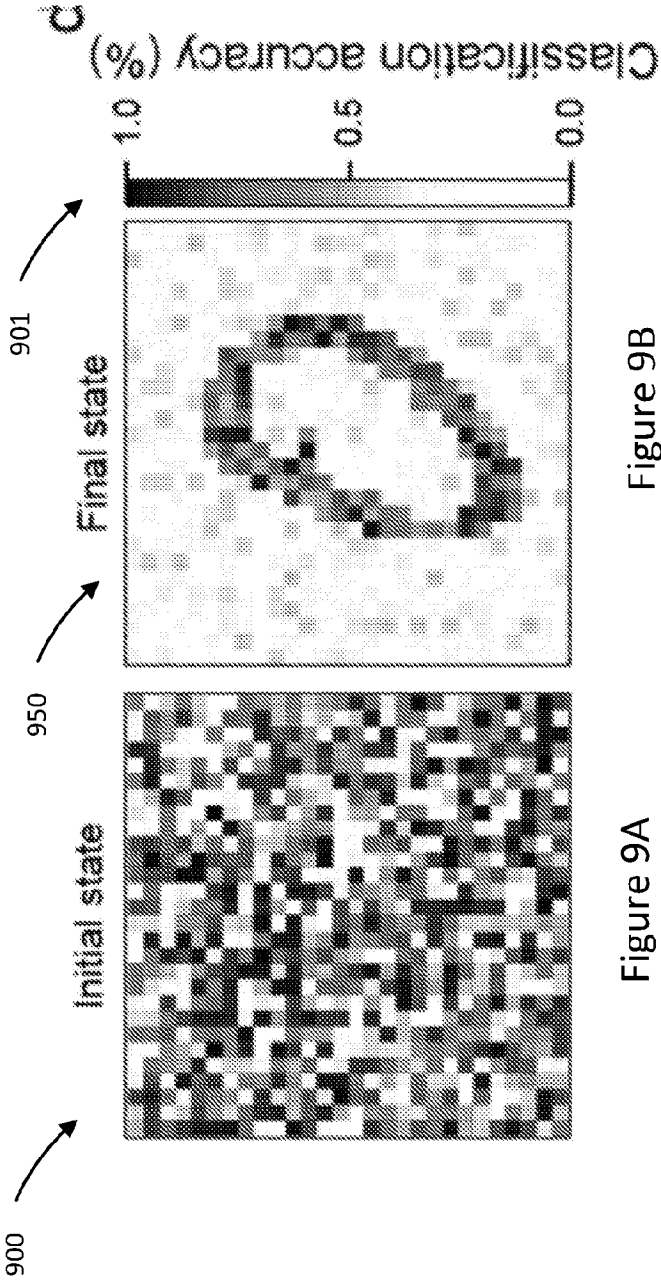


Figure 8



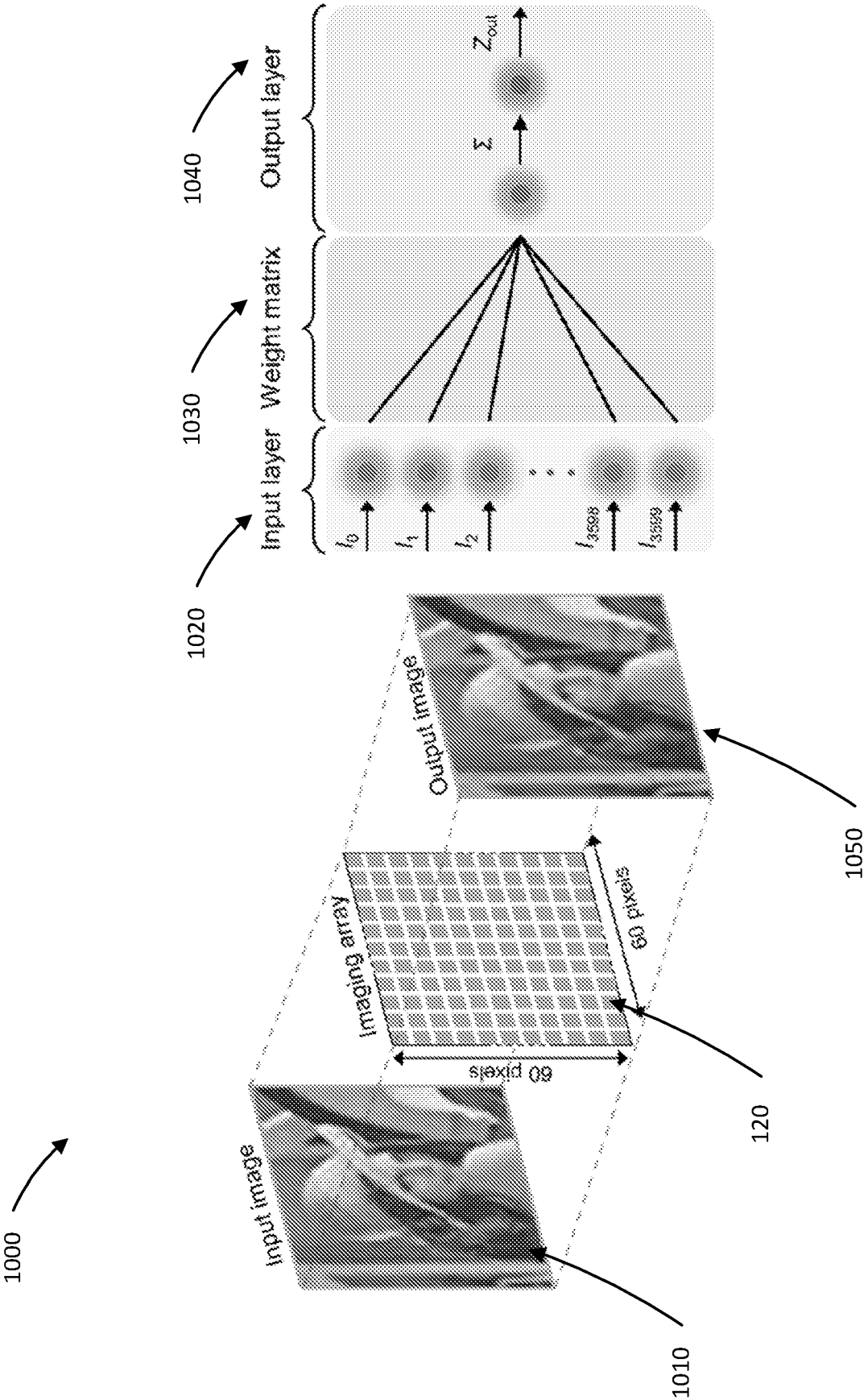


Figure 10

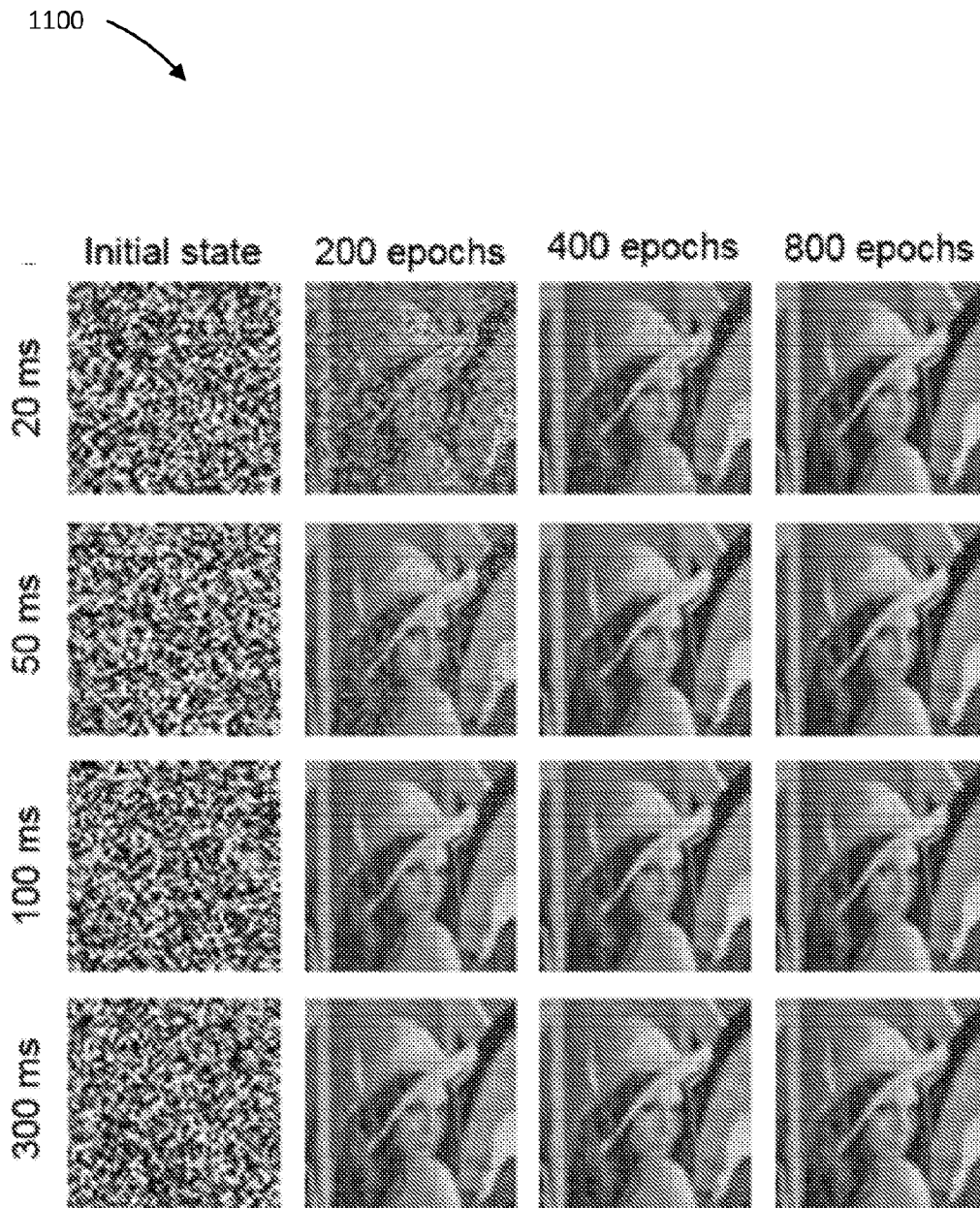


Figure 11

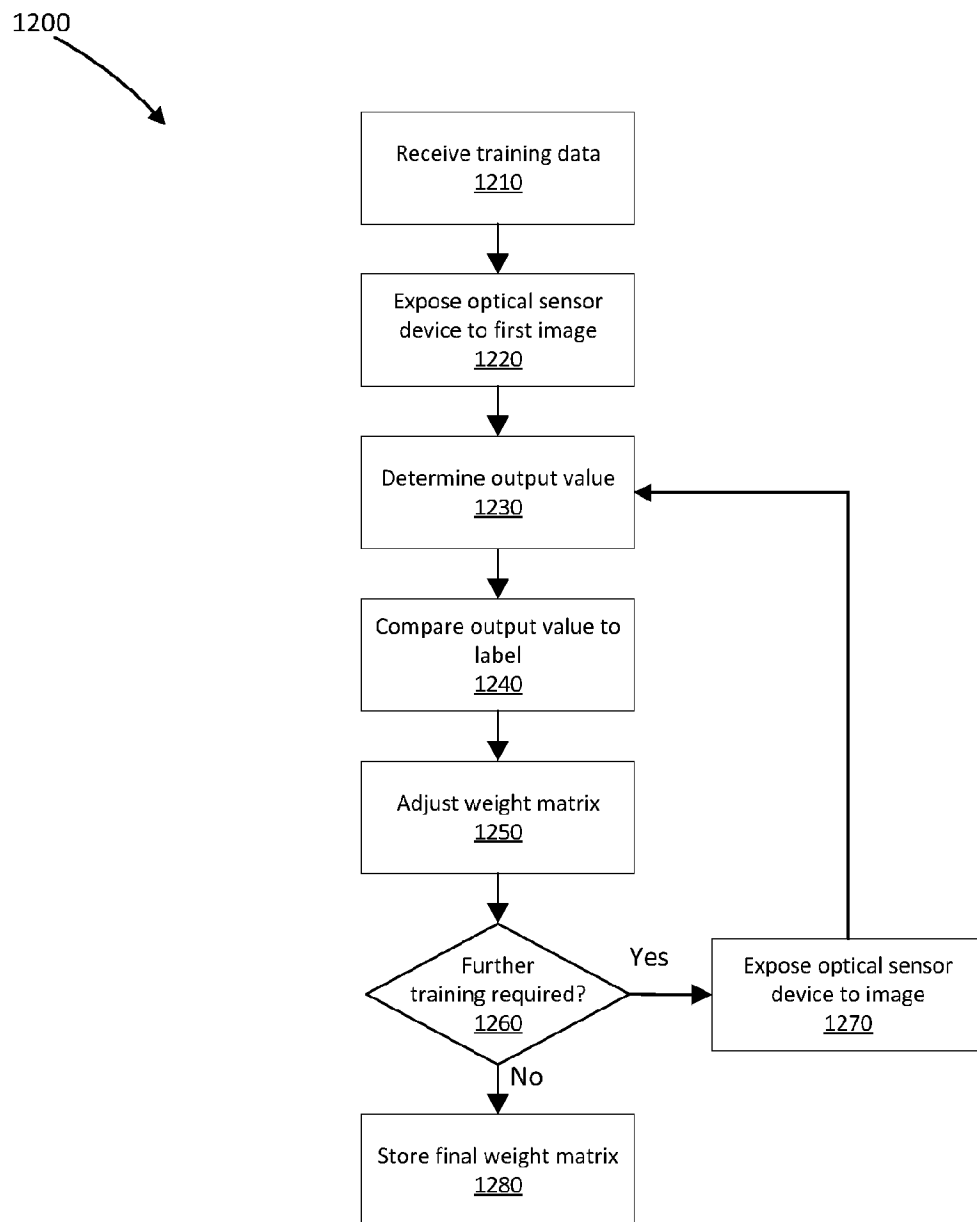


Figure 12

1300

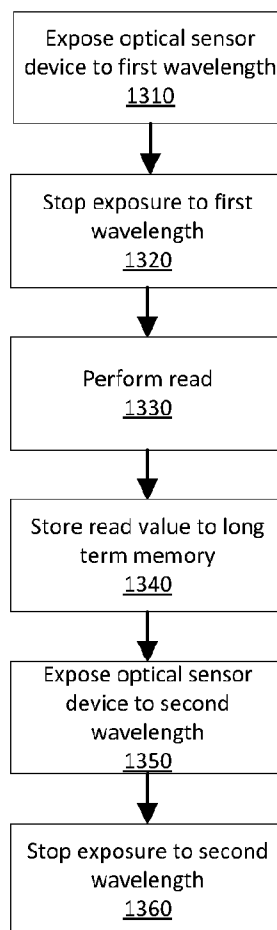


Figure 13

INTERNATIONAL SEARCH REPORT

International application No.

PCT/AU2021/051331

A. CLASSIFICATION OF SUBJECT MATTER

H01L 31/101 (2006.01) H01L 27/144 (2006.01) H01L 31/167 (2006.01) H01L 31/09 (2006.01) H04N 5/235 (2006.01)
H04N 5/335 (2011.01) H04N 21/4223 (2011.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Databases: PATENW, INSPEC, Espacenet, Google Patents, Google, Google Scholar; CPC/IPC Symbols H01L27/144, H01L31/14, H04N5/2353, H04N21/4223, H01L31/14, H04N5/235, H04N5/335, H01L31/101, H01L31/09, H01L31/167; Keywords: photo sensor light controlled memory effect, camera sensor photo-memory EM radiation, camera sensor storing image, "camera" optoelectronic sensor light "memory", shutter, block, threshold time, train, neural network, read data, training image, label, weight matrix wavelength dependent conductance, short-term memory, Neuro robotics, human-machine interaction, bionic application, neuro-morphic computing and like terms. Applicant/Inventor name(s) were searched in DOCDB, DWPI & internal databases provided by IP Australia.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	

☒ Further documents are listed in the continuation of Box C☒ See patent family annex

* Special categories of cited documents:	
"A" document defining the general state of the art which is not considered to be of particular relevance	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"D" document cited by the applicant in the international application	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier application or patent but published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search
3 February 2022

Date of mailing of the international search report
03 February 2022

Name and mailing address of the ISA/AU

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INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		PCT/AU2021/051331
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Zhou, F. et al, ' 2D Materials Based Optoelectronic Memory: Convergence of Electronic Memory and Optical Sensor', Department of Applied Physics, The Hong Kong Polytechnic University, Hong Kong, Research, Published 21 August 2019, https://www.researchgate.net/publication/335357127_2D_Materials_Based_Optoelectronic_Memory_Convergence_of_Electronic_Memory_and_Optical_Sensor Abstract, figs. 2, 4, 5, 6, 7, 9, 10, Table 1, Sections: 1. Introduction, 2.2D Materials Based Nonvolatile ORAM, 3.2. 2D Materials Based ORAM, 3.3. 2D Heterostructure Based Nonvolatile ORAM, 4. 2D Materials Based ORAM Synaptic Device, 5. Conclusions and Perspectives	1-14
X	US 2019/0306391 A1 (PHOTOPOTECH LLC) 03 October 2019 Abstract, figs. 4, 5, 7; paras [0047], [0070-0071], [0082-0083], [0098-0100], [0141], [0149-0153], [0179-190], [0195-0200], [0209-210]	1-14
X	Yan, F. et al, 'Toward High-Performance Photodetectors Based on 2D Materials: Strategy on Methods', Small Methods, published November 2017. https://www.researchgate.net/publication/324018499_Toward_High-Performance_Photodetectors_Based_on_2D_Materials_Strategy_on_Methods see whole document, especially sections: 1. Introduction, 3. Strategies for Enhancing the Performance of Photodetectors, figs 1, 3, 4, 6, 7	1-14
X	WO 2018/234215 A1 (LIFE TECHNOLOGIES GMBH) 27 December 2018 Abstract, figs. 1, 3, 7, 8, paras [0007-0009], [0028-0029], [0034], [0055- 0065], [0075], [0085-0089], [0105], [0143-0150]	1-14
A	Tan, H. et al, 'Switching Memory: An Optoelectronic Resistive Switching Memory with Integrated Demodulating and Arithmetic Functions', DOI: 10.1002/adma.201500039, Adv. Mater. 2015, 27, 2797–2803 , published 2015. https://www.researchgate.net/publication/273783326_Switching_Memory_An_Optoelectronic_Resistive_Switching_Memory_with_Integrated_Demodulating_and_Arithmetic_Functions_Adv_Mater_172015 see whole document	1-23
X	CN 111355901 A (UNIV PEKING SHENZHEN GRADUATE SCHOOL) 30 June 2020 Summary of the invention, Detailed description, figs. 2(a), 2(b), 3(b), 4, 5, 9	15-20
X	Shao, Z. et al. 'Memory phototransistors based on exponential-association photoelectric conversion law', Nat Commun 10, 1294, Published: 20 March 2019. https://www.nature.com/articles/s41467-019-09206-w see whole document more specifically Abstract, Introduction, Results, figs. 1-5	15-20
X	US 2017/0013210 A1 (PIXART IMAGING INC.) 12 January 2017 abstract, figs. 2-5, 7, 10-11, paras [0010-0015], [0029-0032], [0036-0060]	15-20
Form PCT/ISA/210 (fifth sheet) (July 2019)		

INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		PCT/AU2021/051331
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	Chapinal, G. et al. 'A 128 x 128 CMOS Image Sensor With Analog Memory for Synchronous Image Capture', Sensors Journal, IEEE. 2. 120 - 127. 10.1109/JSEN.2002.1000252, published May 2002. https://www.researchgate.net/publication/3430989_A_128_x_128_CMOS_Image_Sensor_With_Analog_Memory_for_Synchronous_Image_Capture	1-23
Form PCT/ISA/210 (fifth sheet) (July 2019)		

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
the subject matter listed in Rule 39 on which, under Article 17(2)(a)(i), an international search is not required to be carried out, including
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

See Supplemental Box for Details

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☒ No protest accompanied the payment of additional search fees.

Supplemental Box**Continuation of: Box III**

This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept.

This Authority has found that there are different inventions based on the following features that separate the claims into distinct groups:

Group I (Claims 1-14): These claims are directed to an imaging device for capturing image data. The features of 'an exposure control device configured to adopt a first mode and a second mode, wherein in the first mode the exposure control device causes electromagnetic radiation to reach the sensor and in the second mode the exposure control device restricts electromagnetic radiation from reaching the sensor; a processor configured to receive sensor data from the sensor, and to cause the exposure control device to selectively adopt the first mode and the second mode' are specific to this group of claims.

Group II (Claims 15-23): These claims are directed to a method of capturing image data. The features of 'upon determining that a threshold period of time has elapsed, causing the sensor to be blocked from electromagnetic radiation; reading data captured by the sensor based on the exposure; and recording the read data to a long term memory device' are specific to this group of claims.

PCT Rule 13.2, first sentence, states that unity of invention is only fulfilled when there is a technical relationship among the claimed inventions involving one or more of the same or corresponding special technical features. PCT Rule 13.2, second sentence, defines a special technical feature as a feature which makes a contribution over the prior art. When there is no special technical feature common to all the claimed inventions there is no unity of invention.

In the above groups of claims, the identified features may have the potential to make a contribution over the prior art but are not common to all the inventions in the groups of paragraphs and therefore cannot provide the required technical relationship. Therefore, there is no special technical feature common to all the inventions in the groups of paragraphs and the requirements for unity of invention are consequently not satisfied *a priori*.

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2021/051331	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
US 2019/0306391 A1	03 October 2019	US 2019306391 A1	03 Oct 2019
		US 10778877 B2	15 Sep 2020
		US 2017154463 A1	01 Jun 2017
		US 10114467 B2	30 Oct 2018
		US 2017155852 A1	01 Jun 2017
		US 10306156 B2	28 May 2019
		US 2017154462 A1	01 Jun 2017
		US 10706621 B2	07 Jul 2020
		US 2021295592 A1	23 Sep 2021
		US 11217009 B2	04 Jan 2022
WO 2018/234215 A1	27 December 2018	WO 2018234215 A1	27 Dec 2018
		CN 110476249 A	19 Nov 2019
		EP 3419053 A1	26 Dec 2018
		EP 3639301 A1	22 Apr 2020
		JP 2020524921 A	20 Aug 2020
		JP 6953552 B2	27 Oct 2021
		JP 2022002407 A	06 Jan 2022
		KR 20200014792 A	11 Feb 2020
		KR 20210146422 A	03 Dec 2021
US 2021143201 A1	13 May 2021		
CN 111355901 A	30 June 2020	CN 111355901 A	30 Jun 2020
		WO 2021184634 A1	23 Sep 2021
US 2017/0013210 A1	12 January 2017	US 2017013210 A1	12 Jan 2017
		US 9686489 B2	20 Jun 2017
		CN 105391947 A	09 Mar 2016
		CN 105391947 B	22 Jun 2018
		TW 201608889 A	01 Mar 2016
		TW I540899 B	01 Jul 2016
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.
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INTERNATIONAL SEARCH REPORT Information on patent family members		International application No. PCT/AU2021/051331	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
		TW 201703511 A	16 Jan 2017
		US 2016065866 A1	03 Mar 2016
		US 9661250 B2	23 May 2017
End of Annex			
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001. Form PCT/ISA/210 (Family Annex)(July 2019)			