Title: CMOS IMAGE SENSOR HAVING HYBRID PIXEL ARRAYS

Abstract: Embodiments of the present invention relate to systems and methods for high speed, high resolution imaging, which includes a micropixel array that includes, at least one macropixel, and a macropixel selector module; a micropixel array which is coupled to the macropixel array and includes at least one micropixel, a micropixel selector module, and an analog-to-digital converter; and a global bunch counter.
CMOS IMAGE SENSOR HAVING HYBRID PIXEL ARRAYS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Application No. 60/736,392 filed on November 14, 2005, which is hereby incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present invention relates generally to systems and methods for high-speed, high-resolution imaging.

BACKGROUND OF THE INVENTION

[0003] Throughout history, scientists have been interested in measuring and characterizing subatomic particles. In modern times, scientists have designed various devices for studying these particles.

[0004] One approach has been the use of systems which incorporate pixels to collect and integrate, for example, electron charges or hole charges and convert them into corresponding voltage signals. These detector systems then read out the voltage signal from the pixels that are hit by the particles to obtain information about the particles.

[0005] Early detector systems could not read out the signal in time for the next particle's arrival. As a result, the systems could not distinguish among the particles because the signals became mixed.

[0006] Scientists circumvented this problem by stopping the system during the readout of a signal from the detector, and then proceeding to the next collision. It normally takes, however, a long time - on the order of several seconds - to read out the signal from the entire pixel array. This stop-and-go method limits the exploration of the particle physics in many ways.
Conventional detectors of comprise macropixel arrays adapted to operate at high speeds, but produce low-resolution data. Still other conventional detectors comprise micropixel arrays and provide high resolution data, but read pixel-by-pixel to determine which micropixels on the contain event data is time-consuming and inefficient, resulting in low speed imaging.

Thus, there is a need for an imaging system that operates continuously by reading out information only from those pixels which have been hit by the particles. Such a system would make the overall readout speed much faster and quickly complete the readout process and prepare the detector for a subsequent round of collisions, thereby providing high-speed, high-resolution imaging.

**SUMMARY OF INVENTION**

The above-described problems are addressed and a technical solution is achieved in the art by a system and method that achieves high-speed, high-resolution imaging by providing a macropixel array and an associated micropixel array that communicate with one another to read out only data from micropixels associated with macropixels that have been impacted by one or more particles.

Embodiments of the present invention relate to systems and methods for high speed, high resolution imaging, including detecting an event on a macropixel located in a macropixel array, storing on the macropixel a timestamp and event data associated with the event, detecting an event on a micropixel located in a micropixel array, storing on the micropixel event data associated with the intensity of the event, interrogating the macropixel array to determine a location of the timestamp, identifying a region of interest on the micropixel array which corresponds to the macropixel having the timestamp, wherein the region of interest comprises a plurality of micropixels, integrating event data from the macropixel array with the event data.
from the corresponding region of interest on the micropixel array to generate integrated data, and reading out the integrated data.

BRIEF DESCRIPTION OF THE DRAWINGS

[00011] The present invention will be more readily understood from the detailed description of the embodiments presented below, considered in conjunction with the attached drawings, of which:

[00012] FIG. 1 is an illustration of an exemplary hybrid detector system, according to embodiments of the present invention;

[00013] FIG. 2A and 2B is a side view of a hybrid sensor having a micropixel array bonded to a micropixel array, according to embodiments of the present invention;

[00014] FIG. 3 is an overview of the architecture of a macropixel array according to embodiments of the present invention;

[00015] FIG. 4 is an overview of the architecture of a macropixel according to embodiments of the present invention;

[00016] FIG. 5 is an overview of the architecture of a micropixel array according to embodiments of the present invention; and

[00017] FIG. 6 is an overview of the architecture of a micropixel according to embodiments of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[00018] The present invention relates to an imaging system and method that achieves high-speed, high-resolution imaging by providing a macropixel array and an associated micropixel array that communicate with one another to produce data relating to an event detected by the system. The term "event", as it is used herein, is intended to include the occurrence of an
interaction between a particle and the macropixel. The term "particle", as it is used herein, is intended to include but is not limited to, any unit of matter or energy, including but not limited to any molecule, atom, subatomic particle (including but not limited to a proton, neutron, electron or quark), photon, colloid particle, elementary particle, composite particle or point particle. In embodiments of the present invention, an event is detected by both the macropixel array and the micropixel array. The event data generated by the macropixel array is used by a control system to determine a region of interest on the micropixel array. Event data from the micropixel array relating to the intensity of the event is integrated with event data from the macropixel array relating the time and x, y location of the event to generate integrated event data. The integrated event data is read out from the control system and output to a camera or other device capable of reading the data. The term "event data", as it used herein, includes information concerning the impact of the particle upon the hybrid detector 100 according to embodiment of the present invention and includes, but is not limited to, any imaging data or characteristic storable in a pixel such as, for example, the position and intensity associated with the impact of the particle, i.e., event.

[00019] FIG. 1 illustrates an overview of the hybrid detection system 100 according to an embodiment of the present invention. The detection system includes a macropixel array 102 comprising one or more macropixels 106 and an associated micropixel array 104 comprising one or more micropixels 108. Further, the system includes a control system 112 that integrates event data generated by the macropixels 106 and the micropixels 108. According to embodiments of the present invention, a macropixel 106 on the macropixel array detects an event and conveys the time and position of the event to a control system 112. The control system 112 determines a "region of interest" on the micropixel array 104. As it is used herein, the term "region of
interest" is intended to include a region on the micropixel 108 which corresponds to the macropixel 106 that detected the event. The control system 112 collects intensity data from the region of interest on the micropixel array 104 and generates event data.

[00020] FIG. 2A and 2B illustrate that two sensor arrays, a macropixel array 102 and a micropixel array 104 are bonded and are impacted by one or more particles 302 that impact the macropixel array 102. One having skill in the art will understand that any suitable bonding method and bonding material may be used in accordance with the present invention. For example, the arrays may be bonded by welding, adhesive glues, interlocking parts, electrostatic forces, etc.

[00021] With respect to the macropixels in the macropixel array, in some embodiments of the present invention, the individual macropixels 106 may be on the order of approximately 1-1000 micrometers. Due to their relatively large size, these macropixels 106 provide low-resolution imaging. However, the macropixel array 102 according to embodiments of the present invention is structured such that it may be scanned, interrogated or read out at high speed and to output digital information relative to individual particles 302 striking the macropixel array 102 including data regarding position and time.

[00022] With respect to the micropixels in the micropixel array, in some embodiments of the present invention, the individual micropixels 108 may be on the order of approximately 0.01-20 micrometers. Due to their relatively small size, these micropixels 108 provide high-resolution imaging. When a particle 302 strikes the system according to embodiments of the present invention, the micropixel array 104 detects the analog signal proportional to the intensity of the energy of the particle 302.
FIG. 3 represents the operation and architecture of a macropixel array 102 according to embodiments of the present invention. The macropixel array 102 consists of a plurality of macropixels 106, a macropixel selector module, a multiplexer (MUX) 506, a global bunch counter 508, and a timing controller 510. As described below, the macropixel row selector and the macropixel column selector interrogate the macropixel array to determine the location of any macropixel that may contain a timestamp. The macropixel selector module includes a macropixel row selector (i.e., a macro pixel vertical decoder) 502 and a macropixel column selector (i.e., a macro pixel column select logic) 504.

First, upon the happening of an event, the bunch counter 508 increments - synchronized by the external strobe pulse - and its digital output supplies to the entire pixel array using the macropixel array bus (i.e., column data bus). As it is used herein, the term "bus" is intended to include, but is not limited to, any subsystem that transfers data or power between components within an electronic device or component or between electronic devices or components. If any of the macropixels detect the signal due to the particle hit, then the digital value of global bunch counter 508 is loaded in the digital memory cell array 410. In some embodiments of the present invention, the digital memory array 410 is comprised of plurality of conventional flip-flop circuits 414, which are known to those of skill in the art. This bunch counter 508 value represents the timestamp reflecting the time when the particle 302 hit occurred (i.e., the time of the event). Since the macropixel array bus needs to cover the entire macropixel array 102, the capacitive load becomes very large and the system will drive the macropixel array bus slowly. To circumvent this problem, a buffer circuit is used in embodiments of the present invention at every column of the digital macropixel array 102 to reduce the parasitic capacitance of the macropixel array bus.
Next, the macropixel row selector 502 selects one row line after another synchronized by the timing pulse supplied from timing controller 510. This enables the macropixels 106 to be read out sequentially or randomly. To speed up the readout procedure, the macropixel row selector 502 selects one row of macropixels 102 and first interrogates the macropixels 102 to determine whether any of the flip-flops 414 have been written in a macropixel 102. This operation is a simplified by reading out of the row counter 408 value or a flag signal "empty" that represents the null state of the row counter 408 first in the macropixel 102. A zero value of the content of the counter or "on" state of the "empty" flag signal implies there has been no event experienced by the macropixel 106 during the last integration time. Then, the macropixel row selector 502 and macropixel column selector 504 skip to next pixel instead of spending time to read out the contents of the empty digital macropixel array 102. This approach reduces the readout time significantly. If a pixel contains a non-zero counter, or "off" state, then it reads out the memory for only those macropixels 106 that experienced an event (i.e., those having a timestamp). If none of the macropixels in the selected row issue the "empty" flag, the macropixel column selector 504 is supposed to readout the timestamps sequentially operating multiplexing switches column by column by. If a few of the macropixels 106 in the, selected row issue an "empty" flag, the macropixel column selector skips the columns where the "empty" flag signal is "on", and stops at the columns where the "empty" flag signal is "off" and read out the timestamp data. If all of the macropixels in the selected row issue the "empty" flag, the macropixel column selector skips entire columns and makes macropixel row selector 502 proceed to next row selection. One having ordinary skill in the art will appreciate that any suitable digital memory device or circuit may be used in accordance with the present invention.
As shown in FIG. 4, the exemplary embodiment described herein includes a digital memory comprising a plurality of flip-flop circuits as the memory elements.

[00026] In embodiments of the present invention, to store the each set of timestamp data with n-bits, each row of the macropixel array 102 needs to consist of at least $2^n$ memory elements. Additional memory elements can be added for the error checking capability, such as parity check or the cyclic redundancy check (CRC), etc. Latching or writing of timestamp takes places by establishing a connection between the macropixel array bus lines from the global bunch counter 508 output and the memory elements. The global bunch counter 508 output combined with an external strobe pulse enables the switch to connect the macropixel array bus to the memory elements of the corresponding row.

[00027] FIG. 4 represents an exemplary macropixel 106 according to an embodiment of the present invention. The macropixel 106 is configured to detect one or more events. As described above, the term "event" refers to the occurrence of an interaction between a particle 302 and the macropixel 106. As discussed in detail below, the macropixel 106 is configured to detect events and stores a timestamp associated with each individual event.

[00028] The macropixel 106 consists of an event sensor module 416. According to embodiments of the present invention, the event sensor module comprises, includes a macropixel photodiode 402, a reset transistor 404 and a comparator 406. Additionally, the macropixel comprises of a binary counter 408 connected to the event sensor module 416, a digital memory cell array 410, and a logic circuit 412 to select and control the digital memory array 410. In other embodiments of the present invention, the digital memory array 410 operates in three modes, including, but not limited to, latch or write mode, hold mode, and read mode. In other embodiments of the present invention the digital memory array 410 operates in less than three
modes. In further embodiments of the present invention, the digital memory array 410 operates in more than three modes.

[00029] When an particle 302 hits the macropixel 106, the macropixel photodiode 402 collects electrons or holes, depending on the impurity type. Thus, for example, if the photodiode is of the n-type, which is known to those of skill in the art, then electrons are collected in the sensing node. If the signal charge integrated in the macropixel photodiode 402 reaches a threshold level, the comparator 406 output switches from "high" to "low" level, to indicate that an event has occurred. Then, this low signal makes one row of the digital memory array 410 latch the macropixel array bus timestamp input supplied from the global counter circuit in order to load a timestamp associated with the event.

[00030] When the latching is completed, macropixel photodiode 402 is reset to VDD voltage, which is known to those of skill in the art, and comparator 406 output becomes "high", disabling the latch mode for the digital memory array 410. The timestamp information is thus loaded and saved in the digital memory array 410 will then remain saved.

[00031] If a second event is experienced by the same macropixel 106, the binary counter 408 is incremented and its output is used to select the next row of the digital memory array 410, and the new timestamp data associated with the event is loaded into the memory. Thus the macropixel 106 loads a timestamp associated with the second event experienced. This process repeats until the last row of digital memory array 410 completes the latching.

[00032] In order to read out the content of the digital memory array 410, the system according to embodiments of the present invention must reset the row counter 408 to zero and enter into the "read" mode. However, before readout of the content of the flip-flops 414 takes place, the row counter 408 contents must be read out first. This method is useful for interrogating the
macropixel 102 at high speed to determine if a given macropixel has been hit by a particle 302. The macropixel array bus is shared for both reading out and writing by time multiplexing method, in other words, reading and writing do not overlap at any time.

[00033] FIG. 5 illustrates the architecture and operation of a micropixel array 104 according to embodiments of the present invention. The micropixel array includes a region of interest 110, which may be defined to include but is not limited to, an area of one or more micropixels 108 on the micropixel array that are associated with one or more macropixels 106 that have been identified as having detected an event.

[00034] The architecture of a micropixel array 104 consists of a micropixel selector module, a correlated double sampling (CDS) circuit 706, a timing controller 708, an output amplifier 710, an analog-to-digital converter (ADC) 712, and a two-dimensional micropixel array 714. The micropixel selector module NUMBER includes a micropixel row selector (i.e., a micro pixel vertical decoder and driver) 702 and a micropixel column selector (i.e., a micro pixel column select logic) 704.

[00035] To achieve a random access readout, which is known to those of skill in the art, instead of a time-consuming sequential readout, the macropixel row selector 702 decodes the row select line based on the address information supplied by the timing controller 708. Timing controller 708 transfers this address information from the external controller. The micropixel column selector 704 operates in the same fashion. For example, if a user defines a region of interest having a square or rectangular shape of a window in the image array, timing controller 708 translates the window into the starting address and ending address from the x-coordinate and y-coordinates of the window. Then, the system will use the x-address and y-address to determine the scope of its sweep, which will be performed sequentially or in an interlaced...
fashion, to readout the micropixels 108 within the window. Thus, a region of interest may, in embodiments of the present invention, be pre-selected by a user.

[00036] In embodiments of the present invention, the CDS circuit 706 is used at every column to eliminate fixed pattern noise due to the offset variation. The signal output of the each column's CDS circuit 706 is multiplexed to one micropixel array bus and amplified and digitized by the ADC 712. One having ordinary skill in the art will appreciate that any suitable CDS circuit may be used in accordance with the present invention. On having ordinary skill in the art will appreciate that the macropixel array bus and the micropixel array bus may be the same or different physical components.

[00037] FIG. 6 illustrates the architecture and operation of a micropixel 108 according to embodiments of the present invention. As described below, the micropixel 108 stores data related to the intensity of the event. Position or coordinates information of the pixel is obtained from the micropixel row selector and the micropixel column selector 704 of the micropixel array 102.

[00038] A micropixel 108 according to embodiments of the present invention consists of a micropixel photodiode 602, a reset transistor 604, a source follower transistor 606 and a row select transistor 608. This architecture is based on the use of conventional pixel architecture to leverage the small pixel's size to achieve high-resolution.

[00039] With respect to the operation of the micropixel 108 according to embodiments of the present invention, when particle hits the silicon lattice near the micropixel photodiode 602, electrons and holes are generated. Electrons are collected and potential changes as a function of integrated charges in the photodiode 602. Then, the signal from the micropixel photodiode 602 is read out by the source follower transistor 606 when the row select transistor 608 is enabled.
The role of the reset transistor 604 is to reset the photodiode potential to its original state at VDD.

[00040] As demonstrated below, the macropixel array 102 and the micropixel array 104 work interactively in embodiments of the present invention to achieve high-speed, high-resolution two-dimensional capture of particle 302 trace.

[00041] Upon impact by a particle 302 on a macropixel 106 according to embodiments of the present invention, the photodiode 402 signal rises above the threshold level and comparator 406 output switches from '1' to '0', enabling the loading of a global timestamp into one row of the digital memory cell array 410. It is to be noted that the designations '1' and '0' are simply used as relative terms and any relative terms or designations may be used in embodiments of the present invention. When the loading the timestamp data in the digital memory cell array 410 is completed, macropixel photodiode 402 resets and comparator output 406 switches back to '1'. Next, upon impact by another particle 302 upon the same macropixel 106, a different timestamp will be loaded into the next row of the digital memory cell array 410.

[00042] Upon impact of the particle 302, the micropixel photodiode 602 also integrates the signal charge generated by the impact of the particle 302. However, the charges remain in the micropixel photodiode 602, instead of reading out data or resetting until the end of the bunch train. When another particle 302 hits the same pixel, the charges accumulate in the micropixel photodiode 602 and signal charge quantity increases.

[00043] When all particle 302 impacts have ceased for a pre-selected time frame, the macropixel array 102 starts interrogation of each macropixel 106 to determine if there is any timestamp loaded in the digital memory cell array 410.
If a macropixel 102 having a non-zero value on its counter 408 is found, the content of the digital memory cell array 410 is read out. At the same time, current status of the macropixel row selector 502, and the macropixel column selector 504 represent the x, y coordinates of the macropixel 106.

Based on the low resolution x, y coordinates of the macropixel 106, starting and ending addresses of the window are generated to read out high resolution x, y coordinates of the micropixel 108 as well as the intensity of the micropixel signals within the window.

Each of the micropixels 108 are read out, digitized and sent to a camera system or other system or device capable of processing pixel data. Since only a select number of micropixels 108 are read out, high-speed, high-resolution results are achieved. After the micropixel signal is read out, the micropixel photodiode 602 is reset to VDD voltage.

Thus, the hybrid detector system according to embodiments of the present invention combines two different arrays, macropixel arrays 102 and micropixel arrays 104. The macropixel stores the timestamp information associated with an event (i.e., when a particle hits the detector). It includes digital memory cell arrays 410 to store multiple timestamps so that the system can record several events. In embodiments of the present invention the micropixel 108 embedded in the macropixel 106 is based on CMOS APS architecture. Since its size is small, it is capable of yielding high resolution. By combining multiple timestamp capturing capability and high resolution imaging capability, the hybrid pixel system is able to translate the particle events into 3-D information, i.e., x, y coordinates plus time scale. Moreover, the hierarchical architecture according to embodiments of the present invention handles the information in a smart way by decimating unnecessary data at the front end, instead of carrying "garbage" information along during the readout process. This relieves the tremendous bandwidth burden of
the system, thereby relaxing the readout speed. This relaxed speed also is beneficial for reducing
the power consumption and for improving EMI (electro-magnetic interference) robustness.

[00048] It is to be understood that the above-described embodiments are merely illustrative of
the present invention and that many variations of the above-described embodiments can be
devised by one skilled in the art without departing from the scope of the invention. It is therefore
intended that such variations be included within the scope of the following claims and their
equivalents.
CLAIMS

What is claimed is:

1. A method for high-speed, high-resolution imaging, comprising the steps of:
   detecting an event on a macropixel located in a macropixel array and on a micropixel located in a micropixel array;
   storing on the macropixel a timestamp and data associated with the event;
   storing on the micropixel data associated with the event;
   interrogating the macropixel array to determine a location and timestamp associated with the event;
   identifying a region of interest on the micropixel array based on the location and timestamp data, wherein the region of interest comprises a plurality of micropixels;
   interrogating the plurality of micropixels of the region of interest to obtain data associated with the event;
   integrating the data from the macropixel array with the data from the region of interest to generate integrated data; and
   reading out the integrated data.

2. The method of claim 1, further comprising the steps of:
   detecting a second event on the macropixel and on the micropixel;
   incrementing a binary counter on the macropixel;
   storing on the macropixel a timestamp and data associated with the second event;
   storing on the micropixel data associated with the second event;
   interrogating the macropixel array to determine a location and timestamp associated with the second event;
identifying a region of interest on the micropixel array based on the location and
timestamp data, wherein the region of interest comprises a plurality of micropixels;
interrogating the plurality of micropixels of the region of interest to obtain data
associated with the second event;
integrating the data from the macropixel array with the data from the region of
interest to generate integrated data; and
reading out the integrated data.
3. The method of claim 1, wherein in the macropixel array is interrogated by means of a
macropixel row selector and a macropixel column selector located on the macropixel
array.
4. The method of claim 1, wherein the data from the at least one micropixel is read out by
means of a micropixel row selector and a micropixel column selector located on the
micropixel array.
5. The method of claim 1, further comprising sending the integrated data to an output.
6. The method of claim 2, wherein the output is a camera.
7. The method of claim 1, wherein the at least one macropixel includes an at least one
digital memory cell array.
8. The method of claim 7, wherein the timestamp is stored on the digital memory cell array.
9. The method of claim 1, wherein the at least one macropixel is 1-1000 micrometers in
size.
10. The method of claim 1, wherein the at least one micropixel is 0.01-20 micrometers in
size.
FIG. 4

COLUMN DATA BUS (BUNCH COUNTER, 1-3000)