(12) **United States Patent**
Fossum

(10) **Patent No.:** **US 9,225,918 B1**
(45) **Date of Patent:** **Dec. 29, 2015**

(54) **IMAGE SENSOR HAVING SUB-DIFFRACTION-LIMIT PIXELS**

(71) Applicant: **Rambus Inc.**, Sunnyvale, CA (US)

(72) Inventor: **Eric R. Fossum**, Wolfeboro, NH (US)

(73) Assignee: **Rambus Inc.**, Sunnyvale, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 225 days.

(21) Appl. No.: **14/056,752**

(22) Filed: **Oct. 17, 2013**

Related U.S. Application Data

(63) Continuation of application No. 11/442,458, filed on May 26, 2006, now Pat. No. 8,648,287.

(60) Provisional application No. 60/685,216, filed on May 27, 2005.

(51) **Int. Cl.**
H01L 27/00	(2006.01)
H04N 5/351	(2011.01)
H04N 5/353	(2011.01)

(52) **U.S. Cl.**
CPC *H04N 5/351* (2013.01); *H04N 5/353* (2013.01)

(58) **Field of Classification Search**
CPC H04N 5/353; H04N 5/3696; H04N 5/3745
USPC .... 250/208.1, 214 R; 348/294, 302, 308, 348/332; 382/284, 299, 303
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,446,373 A	5/1984	Denholm et al.
5,515,181 A	5/1996	Iyoda et al.

5,535,147 A	7/1996	Jacobs et al.
5,633,958 A	5/1997	Kato
5,665,959 A	9/1997	Fossum et al.
5,786,623 A	7/1998	Bergemont et al.
5,867,215 A	2/1999	Kaplan
5,909,026 A	6/1999	Zhou et al.
5,949,483 A	9/1999	Fossum et al.
5,956,141 A	9/1999	Hayashi
6,097,022 A	8/2000	Merrill et al.
6,240,219 B1	5/2001	Gregory
6,296,387 B1	10/2001	Guillemaud
6,313,455 B1	11/2001	Afghahi
6,552,745 B1	4/2003	Perner
6,552,746 B1	4/2003	Yang et al.
6,665,012 B1	12/2003	Yang et al.
6,665,013 B1	12/2003	Fossum et al.
6,704,046 B2	3/2004	Dyas et al.

(Continued)

FOREIGN PATENT DOCUMENTS

WO	WO-2004/099865 A2	11/2004

OTHER PUBLICATIONS

"New Sony Sensor Achieves Industry Smallest Pixel Size," May 25, 2010, http://www.dcviews.com/press/sony-14mp.htm, p. 1-2. 2 pages.

(Continued)

Primary Examiner — Kevin Pyo
(74) *Attorney, Agent, or Firm* — Charles Shemwell
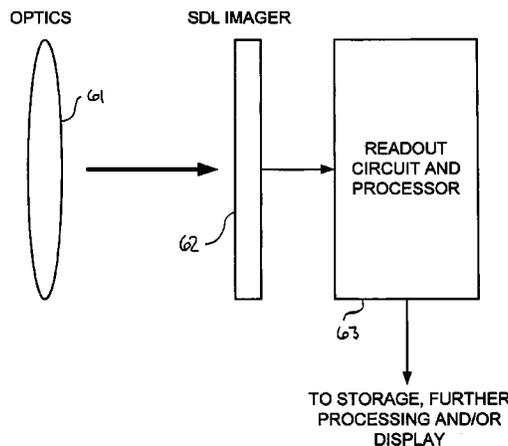
(57) **ABSTRACT**

An imaging system has an imager comprising a plurality of jots. A readout circuit is in electrical communication with the imager. The readout circuit can be configured to facilitate the formation of an image by defining neighborhoods of the jots, wherein a local density of exposed jots within a neighborhood is used to generate a digital value for a pixel of the image.

20 Claims, 4 Drawing Sheets

OPTICS   SDL IMAGER

61

READOUT
CIRCUIT AND
PROCESSOR

62

63

TO STORAGE, FURTHER
PROCESSING AND/OR
DISPLAY

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,791,611 B2	9/2004	Yang	
7,023,369 B2	4/2006	Bocko et al.	
7,095,439 B2	8/2006	Hammadou	
7,109,488 B2	9/2006	Milton	
7,230,224 B2	6/2007	Kondo et al.	
7,242,478 B1	7/2007	Dombrowski et al.	
7,268,814 B1	9/2007	Pain et al.	
7,630,065 B2	12/2009	Suzuki et al.	
7,858,917 B2	12/2010	Stern et al.	
7,956,912 B2	6/2011	Berezin	
8,648,287 B1 *	2/2014	Fossum	H04N 5/374
			250/206
2001/0024237 A1	9/2001	Osada et al.	
2002/0003201 A1	1/2002	Yu	
2002/0015113 A1	2/2002	Chauvin et al.	
2002/0064789 A1	5/2002	Weiss et al.	
2002/0088952 A1	7/2002	Rao et al.	
2003/0025942 A1	2/2003	Atkinson	
2003/0063487 A1	4/2003	Steckl et al.	
2003/0132365 A1	7/2003	Cartlidge	
2004/0008867 A1	1/2004	Fein et al.	
2004/0036788 A1	2/2004	Chapman et al.	
2004/0041082 A1	3/2004	Harmon	
2004/0066878 A1	4/2004	Seppi	
2004/0096125 A1	5/2004	Alderson et al.	
2004/0159772 A1	8/2004	Cartlidge et al.	
2004/0159773 A1	8/2004	Fein et al.	
2004/0235147 A1	11/2004	Chappell	
2004/0245592 A1	12/2004	Harmon et al.	
2005/0001176 A1	1/2005	Loney et al.	
2005/0012033 A1	1/2005	Stern et al.	
2005/0104003 A1	5/2005	Jarron	
2005/0104632 A1	5/2005	Lettvin	
2005/0285822 A1	12/2005	Reddy et al.	
2006/0072104 A1	4/2006	Engel et al.	
2006/0081887 A1	4/2006	Lyu	
2006/0084195 A1	4/2006	Lyu	
2006/0106306 A1	5/2006	Essner et al.	
2008/0025462 A1	1/2008	Sutko et al.	
2008/0158566 A1	7/2008	Suzuki et al.	
2008/0180784 A1	7/2008	Silverstein et al.	
2009/0135114 A1	5/2009	White et al.	
2009/0152681 A1	6/2009	Zheng et al.	
2010/0127156 A1	5/2010	Yokogawa	
2010/0198061 A9	8/2010	Daghighian et al.	
2010/0320369 A1	12/2010	Koskinen et al.	
2012/0218445 A1	8/2012	Petilli	
2014/0103190 A1 *	4/2014	Lee	H01L 27/14612
			250/208.1

OTHER PUBLICATIONS

"Photodiode", Wikipedia entry, last modified Jan. 17, 2012, http://en.wikipedia.org/wiki/Photodiode. 7 pages.

"Photoelectrons", printed from http://www.thefreedictionary.com/photoelectrons on Jan. 17, 2012. 2 pages.

Acosta-Serafini, Pablo M. et al, "A 1/3″ VGA Linear Wide Dynamic Range CMOS Image Sensor Implementing a Predictive Multiple Sampling Algorithm With Overlapping Integration Intervals", IEEE Journal of Solid-State Circuits, vol. 39, No. 9, Sep. 2004, pp. 1487-1496.

Agranov, G., et al., "Super Small, Sub 2um Pizels for Novel CMOS Image Sensors," 2007 International Image SensorWorkshop, pp. 307-310, Jun. 7-10, 2007. 4 pages.

Bermak, Amine, et al., "A Vision Sensor with On-Pixel ADC and In-Built Light Adaptation Mechanism," Microelectronics Jounal 33 (2002), accepted Jul. 23, 2002. 6 pages.

Davis, Lloyd M., et al., "Imaging of Single-Chromophore Molecules in Aqueous Solution Near a Fused-Silica Interface," Multiphoton Microscopy in the Biomedical Sciences, Proceedings of SPIE, vol. 4262 (2001). 11 pages.

Fairchild Semiconductor Corporation, "Application Note AN-3005 Design Fundamentals for Phototransistor Circuits", 2002. www.fairchildsemi.com/an/AN/AN-3005.pdf. 2 pages.

Fife, K., et al., "A 0.5um Pixel Frame-Transfer CCD Image Sensor in 110nm CMOS," Dec. 2007, Electron Devices Meeting, 2007, IEDM 2007, IEEE International. pp. 1003-1006. 4 pages.

Fitzgerald, AJ, et al., "An Introduction to Medical Imaging with Coherent Terahertz Frequency Radiation," Mar. 2002, Phys. Med. Biol. 47 (2002) R67-R84. 18 pages.

Forchheimer et al., "A Single Chip Linear Array Picture Processor," 1983, Processor, In Applications of digital image processing, SPIE, pp. 425-430. 6 pages.

Forchheimer, Robert, "MAPP2200—A Second Generation Smart Optical Sensor," 1992, SPIE Image Processing and Interchange, vol. 1659, pp. 2-11. 10 pages.

Fortier, Justin et al., "1.2 V O.18um CMOS Imager with Column-Level Oversampling", Department of Electronics, Carleton University, Ottawa, Canada, KIS 5B6. IEEE Solid State Circuits Conference 2001. 4 pages.

Fossum, E. R., "Gigapixel Digital Film Sensor (DFS) Proposal," Nanospace Manipulation of Photons and Electrons for Nanovision 3 Systems, The 7th Takayanagi Kenjiro Memorial Symposium and the 2nd International Symposium on Nanovision Science, University of Shizuoka, Hamamatsu, Japan, Oct. 25-26, 2005, pp. 1-5. 5 pages.

Fossum, E. R., "What to do with Sub-Diffraction-Limit (SDL) Pixels?—A proposal for a Gigapixel Digital Film Sensor (DFS)," IEEE Workshop on Charge-Coupled Devices and Advanced Image Sensors, Jun. 2005, pp. 1-4. 4 pages.

Fossum, Eric R., "CMOS Active Pixel Image Sensors: Past, Present, and Future," 2008, http://ericfossum.com/Presentations/2008%20Jan%20CMOS%20Image%20Sensors%20Past%20Present%20and%20Future.pdf, pp. 1-86. 86 pages.

Fossum, Eric, "Image Sensors Past Present and Future," News Discussion Forum: Digital Photography Review, http://forums.dpreview.com/forums/read.asp? forum=1000&message=28545539, Jul. 7, 2008. 1 page.

Fowler, Boyd et al., "A CMOS Area Image Sensor With Pixel Level A/D Conversion", Information Systems Laboratory, Electrical Engineering Department, Stanford University, Stanford, CA, Jun. 21, 2001. 11 pages.

Goltsman, G.N., et al., "Picosecond Superconducting Single-Photon Optical Detector," Applied Physics Letters, vol. 79, No. 6, Aug. 6, 2001. 3 pages.

Kavusi et al., "Quantitative Study of High Dynamic Range Image Sensor Architectures," 2004, Department of Electrical Engineering, Stanford University, Stanford, CA 94305. 12 pages.

Kavusi, Sam, et al. "Quantitative Study of High Dynamic Range Sigma Delta-based Focal Plane Array Architectures", Department of Electrical Engineering, Stanford University, Stanford, CA 94305, 2004, pp. 341-350.

Kleinfelder, Stuart, et al., "A 10 000 Frames/s CMOS Digital Pixel Sensor," IEEE Journal of Solid-State Circuits, vol. 36, No. 12, Dec. 2001. 11 pages.

Moerner et al., "Methods of Single-Molecule Fluorescence Spectroscopy and Microscopy," Rev. Sci. Instrum. 74, 3597 (2003), American Institute of Physics. 24 pages.

Niclass, Cristiano L., et al., "A CMOS Single Photon Avalanche Diode Array for 3D Imaging," 2004 IEEE International Solid-State Circuits Conference, Feb. 16, 2004, Salon 10-15, Paper 6.7. 10 pages.

Rambus Inc., "Binary Pixel Imager Technology," Jun. 4, 2013, retrieved from hwwp://www.rambus.com/us/technology/innovations/binary-pixel-imager/index.html. 3 pages.

Rhee, Jehyuk, et al., "Wide Dynamic Range CMOS Image Sensor with Pixel Level ADC," Electronics Letters, Feb. 20, 2003, vol. 39, No. 4. 2 pages.

Seitz, Peter, "From Electronic Photography to Seeing Chips—The Future of Image Sensing," Advanced Technologies, Intelligent Vision, 1995. 7 pages.

Yang, David X.D., et al., "A Nyquist Rate Pixel Level ADC for CMOS Image Sensors," IEEE 1998 Custom Integrated Circuits Conference. 4 pages.

Yang, David X.D., et al., "A Nyquist-Rate Pixel-Level ADC for CMOS Image Sensors," IEEE Journal of Solid-State Circuits, vol. 34, No. 3, Mar. 1999. 9 pages.
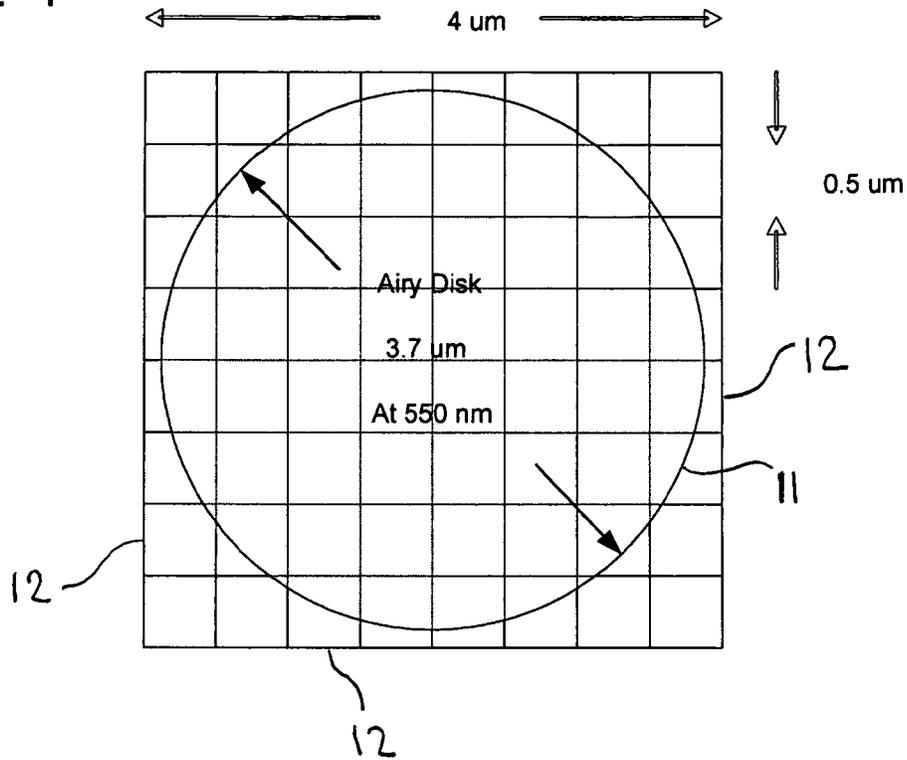
* cited by examiner

Fig. 1

4 um

0.5 um

Airy Disk

3.7 um

At 550 nm

12

11

12

12

Fig. 2

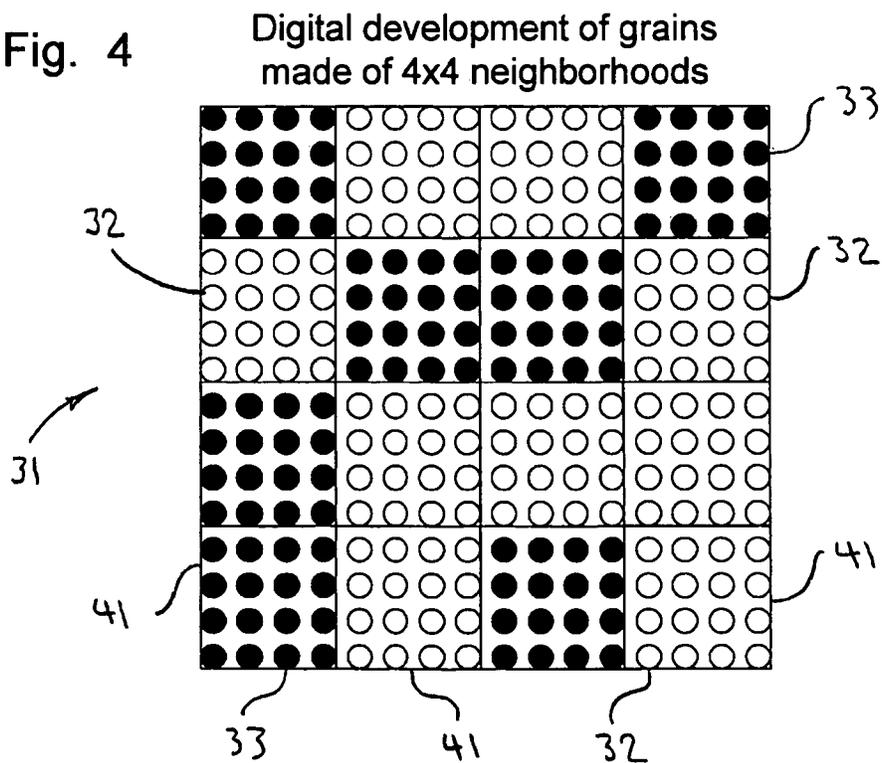**D-LogH Characteristic of Film and Digital Film Sensor**

Fig. 3

Jots with registered photon hits

Fig. 4

Digital development of grains
made of 4x4 neighborhoods

Fig. 5

Region-growing approach for
digital development (3x3)

OPTICS   SDL IMAGER

61

62

READOUT
CIRCUIT AND
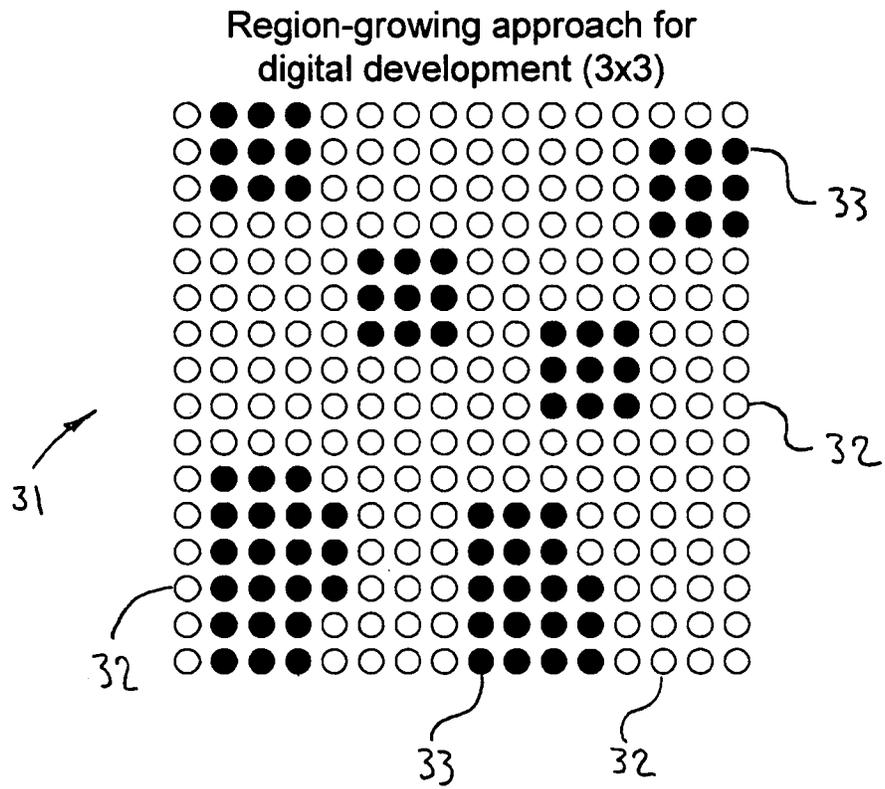PROCESSOR
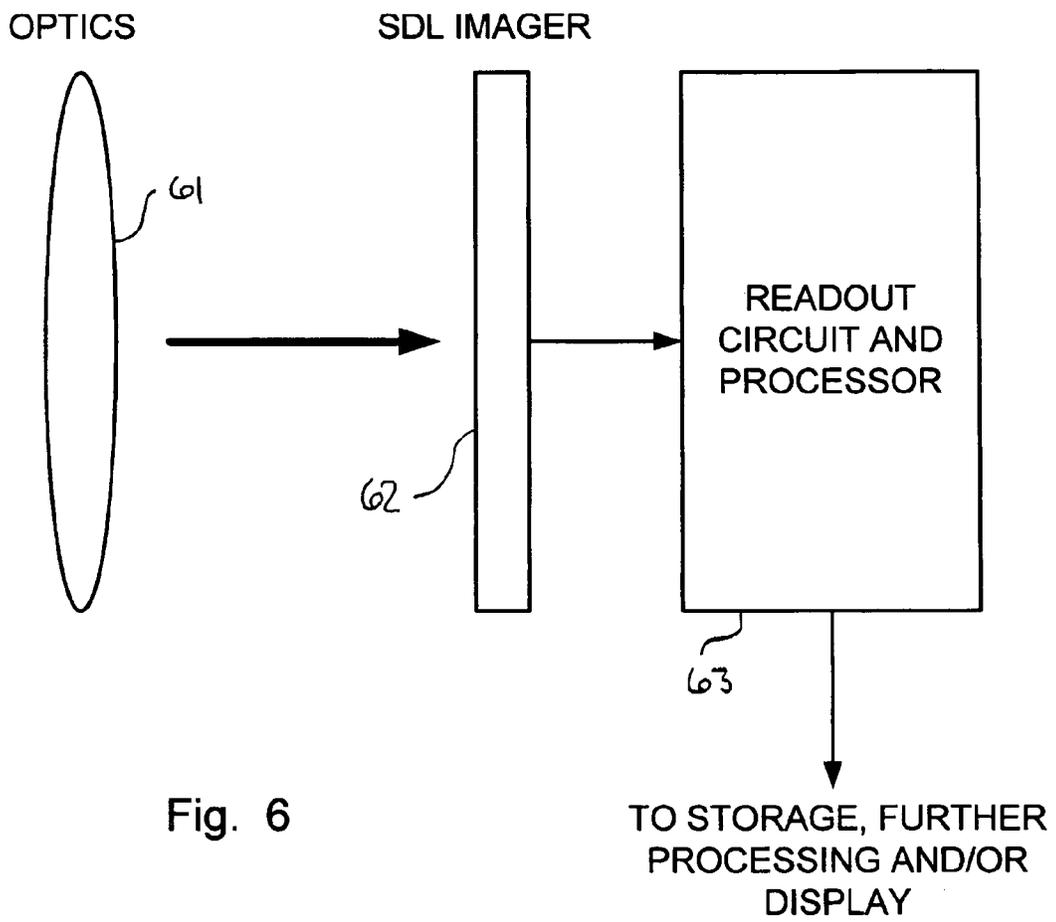
63

Fig. 6

TO STORAGE, FURTHER
PROCESSING AND/OR
DISPLAY
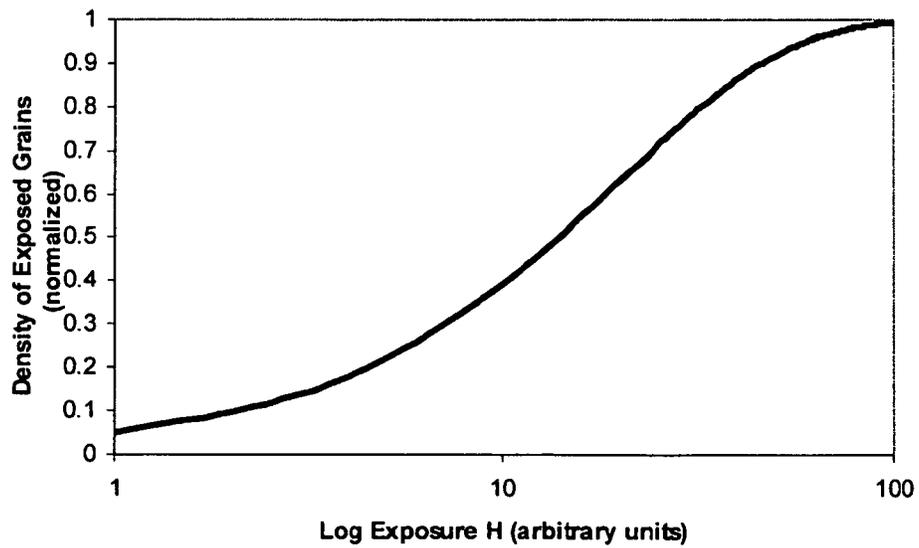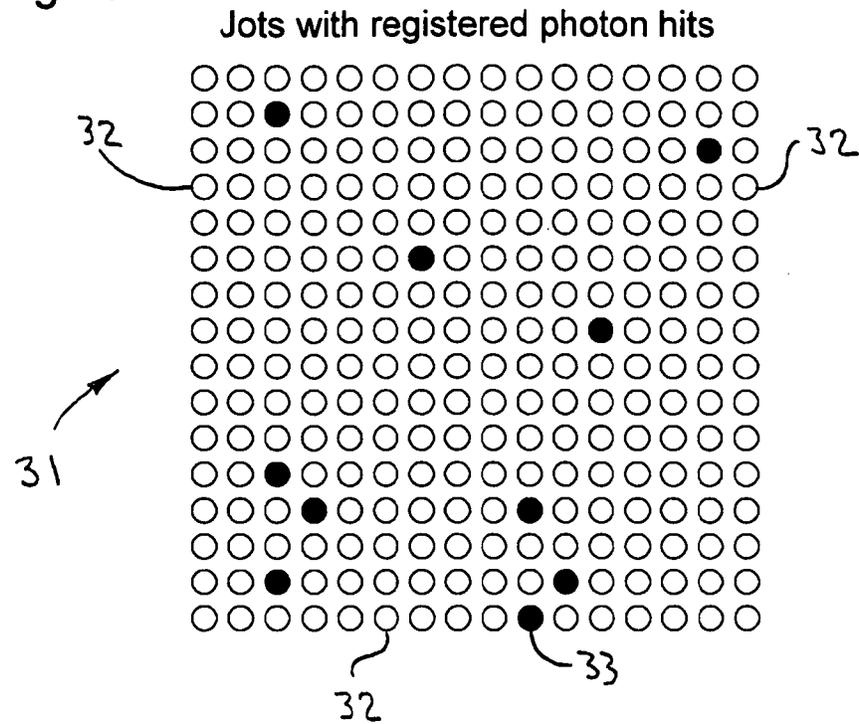
IMAGE SENSOR HAVING SUB-DIFFRACTION-LIMIT PIXELS

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 11/442,458 filed May 26, 2006 (now U.S. Pat. No. 8,648,287), which claims the benefit of U.S. provisional patent application Ser. No. 60/685,216 filed May 27, 2005. Each of the foregoing applications is hereby incorporated by reference.

TECHNICAL FIELD

The present invention relates generally to solid state imaging. The present invention relates more particularly to the use of sub-diffraction-limit (SDL) pixels for imaging, such as to emulate the contemporary silver halide emulsion film process.

BACKGROUND

The relentless drive to reduce feature size in microelectronics has continued now for several decades and feature sizes have shrunk in accordance with the prediction of Gordon Moore in 1975. While the repeal of Moore's Law has been anticipated for some time, we can still confidently predict that feature sizes will continue to shrink in the near future.

Using the shrinking-feature-size argument, it became clear in the early 1990's that it would be possible to put more than 3 or 4 charge coupled device (CCD) electrodes in a single pixel. Thus, the complementary metal oxide (CMOS) active pixel sensor concept was born. The effective transistor count in most CMOS image sensors has hovered in the 3-4 transistor range, and if anything, is being reduced as pixel size is shrunk by shared readout techniques.

The underlying reason for pixel shrinkage is to keep sensor and optics costs as low as possible as pixel resolution grows. Camera size has recently become highly important in the rapidly expanding. camera-phone marketplace. Concomitant with the miniaturization of camera components such as sensors and optics is the miniaturization of optical system components such as actuators for auto-focus and zoom in megapixel camera phones.

We are now in an interesting phase in the development of image sensors for both CCDs and CMOS active pixel sensors. The physical dimensions of the pixel are becoming smaller than the diffraction limit of light at the wavelengths of interest. A perfect lens can only focus a point of light to a diffraction-limited spot, known as an Airy disk and the Airy disk is surrounded by higher order, diffraction rings. The Airy disk diameter D A is given by the equation:

$$DA = 2.44\lambda F\#$$

Where λ is the wavelength and F# is the F-number of the optical system.

For example, at 550 nm, and F-number of 2.8, the Airy disk diameter is 3.7 µm. Yet, pixel sizes in megapixel image sensors are at this size and smaller today. We refer to pixel sizes smaller than the 550 nm Airy disk diameter as sub-diffraction-limit (SDL) pixels.

Today it is readily possible to build a 6-T SRAM cell in less than 0.7 µm² using65 nm CMOS technology. Smaller device are being prototyped. However, significant issues exist for a 0.25 µm² pixel, even though it might be tempting to make a 2 megapixel sensor with 1 mm diagonal using such small pix-

els. For example, the resolution of the sensor would be well beyond the diffraction limit. In fact, over 40 pixels would fit inside the Airy disk and well over a billion pixels (one gigapixel) can fit on a single chip. Although it is possible to construct such an imager, contemporary imagers do not take advantage of this possibility. Further, contemporary practice does not contemplate the best ways to implement such a device.

In view of the foregoing, it is beneficial to provide implementations and practical applications for such SDL pixels. More particularly, it is desirable to provide a method for providing a digital film sensor that emulates, at least to some degree, contemporary silver halide film.

BRIEF SUMMARY

Systems and methods are disclosed herein to provide a digital film sensor (DFS), such as a gigapixel DFS. In this manner, the contemporary silver halide process can, at least to some degree, be emulated.

For example, in accordance with an embodiment of the present invention, an imaging system can comprise an imager having a plurality of sub-diffraction-limit pixels, referred to herein as jots. The imaging system can also comprise a readout circuit that is in electrical communication with the imager. The readout circuit can be configured to form an image by defining neighborhoods of the jots. A local density of exposed jots within a neighborhood can be used to generate a digital value for a single pixel of the image. That is, the digital value can depend upon how many jots within a neighborhood have been exposed (registered a hit by a photon).

A neighborhood can comprise either a single jot or a plurality of jots. Every neighborhood does not necessarily comprise the same number jots. A neighborhood can comprise any desired number of jots. For example, some neighborhoods can comprise one jot, other neighborhoods can comprise two jots, yet other neighborhoods can comprise three jots, and yet other neighborhoods can comprise more than three jots.

A neighborhood can comprise a plurality of jots from a single exposure (a single frame). Alternatively, a neighborhood can comprise a plurality of jots from a plurality of exposures. The number of jots used to define a neighborhood is variable. A jot may belong to one neighborhood for one exposure and to a different neighborhood for another exposure.

The number of jots used to define a neighborhood can be variable according to a region growing process. The number of jots used to define a neighborhood can be variable according to either a spatial or a temporal region growing process. The number of jots used to define a neighborhood can be variable according to both a spatial and a temporal region growing process.

The region growing process can be a process whereby the size of the neighborhood is determined dynamically. That is, various sizes of neighborhoods are tried and the size providing the best results is used to form an image. For example, the size of each neighborhood can be increased until a resolution maximum is defined and the neighborhood size that provides the resolution maximum can be used to form the image. An image can be divided into any desired number of sub-images and the region growing process can be performed independently for each sub-image.

The neighborhoods can have different sizes as a result of this region growing process. For example, neighborhoods comprised of single jots may provide maximum resolution in

one portion of an image, while neighborhoods comprised of four jots may provide maximum resolution in another part of an image.

Each jot can be sensitive to a single photon of light. Alternatively, each jot can require more than one photon to register a hit. The size of the jots within an imager does not have to be uniform. Each jot can be read out as a logical "1" or a logical "0".

The imager can comprise color filters covering a plurality of the jots so as to facilitate color imaging therewith. Different colored filters can cover individual jots or groups of jots in the fashion of the Bayer filters that are used in contemporary color imaging sensors.

A digital processor can be configured to facilitate the generation of the image. Optionally, the digital processor can be integrated on the same chip as the jots. The processor can be configured to use an algorithm to form an image from a jot pattern. The algorithm can be dynamically varied so as to trade spatial resolution for light sensitivity. Thus, when less light is available the number of jots in a neighborhood can be increased. The processor can be configured to use a single or a plurality of readouts of the jots to form a single image.

A jot may comprise an integrating silicon photodetector, a high gain amplifier, a reset circuit, and a selection switch for reading out the jot. The imager can be made using a CMOS-compatible process. Each of the jots can have a total area less than 1 square micron.

A method for digital imaging can comprise setting a grain size digitally. The grain size can be set so as to be the smallest grain size that provides a picture having acceptable quality as measured using a parameter other than grain size. For example, the parameter can be intensity resolution.

The method can comprise digitally developing an image. The method can comprise using a plurality of jots in a manner that provides a desired balance between intensity resolution and spatial resolution. The method can comprise setting a grain size of an imager so as to provide a desired effective International Standards Organization (ISO) speed/resolution. The method can comprise selecting a grain size after exposure so as to enhance image quality. The method can comprise performing a region growing image processing function. The method can comprise determining a jot count of a grain based upon a light level. The method can comprise reading a plurality of jots more than once per exposure. Different jots can be read during each reading thereof.

The method can comprise adding exposures such that grain construct is both spatial and temporal. The method can comprise using different mapping on consecutive readouts so as to dither grain position. The method can comprise varying a grain size during a plurality of readouts of an exposure. The method can comprise mapping light density of exposed jots to define intensity. Light density of exposed jots with overlapping neighborhoods can be mapped to define intensity. Light density of exposed jots with non-overlapping neighborhoods can be mapped to define intensity. The method can comprise mapping jots to define a pixel image.

This invention will be more fully understood in conjunction with the following detailed description taken together with the following drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram showing the relationship between the size of an exemplary Airy disk and exemplary SDL pixels;
FIG. 2 is an exemplary chart showing the density of exposed grains versus exposure for film and digital sensors;

FIG. 3 is a semi-schematic diagram showing an exemplary array of jots according to an embodiment of the present invention, wherein a plurality of the jots have registered photon hits;

FIG. 4 is a semi-schematic diagram showing the array of FIG. 3, wherein the jots have been digitally developed using 4×4 neighborhoods according to an embodiment of the present invention;

FIG. 5 is a semi-schematic diagram showing the array of FIG. 3, wherein the jots have been digitally developed using 3×3 neighborhoods according to an embodiment of the present invention; and

FIG. 6 is a semi-schematic diagram showing an imaging system comprising an SDL imager and a readout circuit/processor according to an embodiment of the present invention.

Embodiments of the present invention and their advantages are best understood by referring to the detailed description that follows. It should be appreciated that like reference numerals are used to identify like elements illustrated in one or more of the figures.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to FIG. 1, the relationship between the size of an exemplary Airy disk 11, e.g., an Airy disk for light having a wavelength of 550 nm, and exemplary sub-diffraction-limit (SDL) pixels 12 is shown graphically. Airy disk 11 has a diameter of 3.7 μm. SDL pixels 12 are square and are 0.5 μm on a side. Of course, the actual size of an Airy disk depends upon the wavelength of light being used to form the Airy disk and the size of the SDL pixels can be larger or smaller than 0.5 μm. As can be seen the Airy disk 11 is substantially larger than each individual SDL pixel 12 and a plurality of SDL pixels 12 can thus fit within Airy disk 11.

According to an embodiment of the present invention, sub-diffraction-limit (SDL) pixels can be used in a new solid-state imaging paradigm. More particularly, SDL pixels can be used in a digital imaging emulation of the well known silver halide emulsion film process. The SDL pixels can be used in a binary mode to create a gigapixel digital film sensor (DFS).

According to an embodiment of the present invention, oversampling of the SDL pixels can be performed. For example, the optical resolution of an image can be highly oversampled. For SDL pixels, such oversampling can mitigate color aliasing problems, such as those that occur due to the use of color filter arrays. Further, a diffraction effect can be used to eliminate the need for anti-aliasing optical filters. For deep-SDL pixels (those SDL pixels having a diameter substantially less than one micron), improved resolution of the optical image can be achieved using digital signal processing.

According to an embodiment of the present invention, SDL pixels are used in the emulation of film. In film, silver halide (AgX) crystals form grains in the sub-micron to the several micron size range. A single photon striking the grain can result in the liberation of a single silver atom. This grain is effectively tagged as exposed and constitutes a latent image. In the subsequent wet chemical development process, the one silver atom results in a runaway feedback process that chemically liberates all the silver atoms in the exposed grain. This liberation of silver atoms leaves an opaque spot in the film, where the silver halide has been converted to metallic silver. Unexposed grains are washed away. The image intensity is thus proportional to a local density of silver grains.

Referring now to FIG. 2, a chart shows the density of exposed grains versus the log exposure thereof for a typical

silver halide emulsion film. As indicted by the chart, the probability that any particular grain is exposed under illumination grows linearly at first, but only eventually approaches unity. This process gives rise to film's particular D-log H contrast curve, where D is density and H is light exposure. The smaller the grain size, the lower the probability that the grain will be struck by a photon in a given exposure, and the slower the film speed will be since more light is required to ensure a high probability that all grains are struck by photons. However, the spatial resolution of the image is determined by grain size, with smaller grain sizes and slower film having higher image resolution.

In a developed film image, the grains are binary-like since they are either exposed or not exposed. The local image intensity is determined by the density of exposed grains, or in digital parlance, by the local spatial density of logical 1's.

According to an embodiment of the present invention, the concept of binary-like development of images in silver halide emulsion film is emulated to provide a digital film sensor (DFS). For example, an embodiment of the present invention can comprise an array of deep-SDL pixels. With sufficiently high conversion gain and sufficiently low readout noise, the presence of a single photoelectron can be determined.

In practice, several photoelectrons can contribute to pushing the output signal above some threshold. However, either single photon or multiple photon sensitivity can be used. From the discussion above, it is evident that a pixel that only needs to detect a single photoelectron has much lower performance requirements for full-well capacity and dynamic range than an analog pixel in a conventional image sensor.

According to one or more embodiments of the present invention, the implementation of a jot can be accomplished is any of several ways. A brute force approach can be to make a conventional active pixel with very high conversion gain (low capacitance). Other approaches include using avalanche or impact ionization effects to achieve in-pixel gain, as well as the possible application of quantum dots and other nanoelectronics devices to define the jots. Stacked structures are also possible, especially since performance requirements are reduced. Of course, it is generally desirable to minimize dark current.

At the start of the exposure period, the jot can be reset to a logical '0'. If the jot is subsequently hit by a photon during an exposure, then the jot is set to a logical '1', either immediately or upon readout. This can be accomplished in a fashion analogous to that performed with memory chips that have been used as image sensors. Due to the single-bit nature of the analog-to-digital conversion resolution, high row-readout rates can be achieved, thus facilitating scanning of a gigapixel sensor having approximately 50,000 rows in milliseconds and thereby enabling multiple readouts per exposure or frame.

The read out binary image can be digitally developed to provide a conventional image having somewhat arbitrary pixel resolution. Such development can be accomplished using a two step process. According to this two step process, image intensity resolution can be traded for spatial resolution.

Referring now to FIG. 3, a representative portion of an exemplary digital film sensor (DFS) can comprise a plurality of jots 32 arranged in an array 31 according to an embodiment of the present invention. Expose jots 33 are indicated as being black. Either one photon or a plurality of photon may be required to expose a jot.

Referring now to FIG. 4, a neighborhood 41 can be defined herein as being comprised of a group of jots. Each neighborhood of FIG. 4 is a 4×4 array of jots. Thus, each 4×4 array of FIG. 4 defines one neighborhood 41. Alternatively, a neigh-

borhood can comprise any other number, e.g., 2, 3, 5, 20, 100, of jots. Indeed, a neighborhood can even comprise a single jot, if desired.

Each neighborhood is at least somewhat analogous to a grain of contemporary silver halide film. The terms neighborhood and grain can thus generally be used interchangeably herein.

According to one embodiment of the present invention, if any jot in a grain or neighborhood 41 has been hit by a photon and is a logical '1', the neighborhood is considered exposed and all jots in the neighborhood are set to '1'. The digital development process allows the flexibility of setting a grain or neighborhood size during readout to adjust the effective speed, e.g. International Standards Organization (ISO) speed of the DFS.

Referring now to FIG. 5, according to an embodiment of the present invention a region-growing approach can be used for digital development. Different sizes of neighborhoods can be tried during an exposure. Alternatively, the size of a neighborhood 41 can be selected to optimize image quality after the exposure.

Thus, the first step of digital development can be performed as a region-growing image processing function. In any case, the development can be accomplished in a jot area-amplification fashion. This first step of digital development can be used in very high jot-count image sensors under low light conditions and corresponds to large-grain film emulsions for very high film speed.

Unlike film where the grain boundaries are fixed during an exposure, it is possible to provide an imaging process where the jots are read out several times during a single exposure. The exposures can be added (logically 'OR'd) together so that the grain construct is both spatial and temporal.

The neighborhood mapping function can be different for each readout. That is, the number and/or location of jots in each neighborhood can be different for each readout. The use of different neighborhood mapping functions for each readout is somewhat analogous to dithering the grain position in a film emulsion during exposure, and perhaps even varying the grain size during the exposure.

In the second step of digital development, the grains which form a binary image can be converted to a conventional digital image that contains pixels with intensity values between 0 and 255, for example. In this case, a local density of exposed grains can be mapped into a pixel image. The more exposed grains in a neighborhood, the higher the pixel value.

Neighborhoods can overlap or can be distinct. If they overlap, this second step is like a blurring convolution process followed by subsampling. At high magnification, a conventional film image appears to be binary due to the presence or absence of silver grains. But, at the lower magnifications used for digitizing film, the same image appears as a continuous gray tone that can be digitized into an array of pixels.

According to an embodiment of the present invention, digital color imaging can be performed in a manner analogous to the procedure used in contemporary color image sensors. Jots can be covered with color filters. Red (R), green (G), and blue (B) jots can be treated separately and later the digitally-developed images combined to form a conventional RGB image. R, G, and B jots need not appear at the same spatial. frequency, and since the deep-SDL nature of the jot pitch results in blurring from diffraction effects, color aliasing is not an issue.

Like film, we expect such a jot-based DFS to exhibit D-log H exposure characteristics. This is true because the physics and mathematics of jot exposure are nominally very similar to

those of film. The dynamic range can be large and the exposure characteristics more appealing for photographic purposes.

The DFS imaging may be superior to contemporary imaging techniques. One or more embodiments of the present invention provide for the use of deep-SDL pixels and introduce a paradigm shift with respect to contemporary solid-state image sensors. Pixel sizes can be measured in nanometers, conversion gain becomes extremely large, charge-handling capacity can be minute, and pixel resolution can be increased by orders of magnitude.

Referring now to FIG. 6, an SDL imaging system is shown. According to an embodiment of the present invention, light from a subject passes through optics 61 and is incident upon SDL imager 62. SDL imager 62 comprises a plurality of jots that can be organized into neighborhoods so as to emulate, at least to a degree, the effect of grain structure in contemporary silver halide film.

Such organization of the jots into neighborhoods can be performed by readout circuit and processor 63, as discussed in detail above. Information from readout circuit and processor 63 can be provided to a memory for storage, to another processor for further processing (color balance, compression, etc.) and/or to a display.

One or more embodiments of the present invention provide applications for SDL pixels. More particularly, one or more embodiments of the present invention provide a method for providing a digital film sensor that emulates, at least to some degree, contemporary silver halide film.

Embodiments described above illustrate, but do not limit, the invention. It should also be understood that numerous modifications and variations are possible in accordance with the principles of the present invention. Accordingly, the scope of the invention is defined only by the following claims.

The invention claimed is:

1. A method of operation within a digital sensor having an array of sub-diffraction-limit (SDL) pixels, the method comprising:

exposing the array of SDL pixels to incident light during a first exposure interval;

reading out first pixel values that indicate respective exposure states of the SDL pixels corresponding to the first exposure interval;

defining a plurality of pixel regions within the array that span respective pluralities of SDL pixels, including setting the quantity of SDL pixels within each of the pixel regions to a first number;

forming a first image containing first digital values that correspond to respective pixel regions of the plurality of pixel regions, including combining the first pixel values read out from the plurality of SDL pixels within each of the pixel regions to generate a respective one of the first digital values.

2. The method of claim 1 further comprising adjusting the quantity of SDL pixels within each of the pixel regions to a second number, forming a second image containing second digital values that correspond to respective pixel regions of the plurality of pixel regions after adjusting the quantity of SDL pixels within each of the pixel regions, comparing the first and second images according to one or more image characteristics, and choosing one of the first and second images to be an output image based on the comparison.

3. The method of claim 2 wherein the one or more image characteristics comprise image resolution.

4. The method of claim 3 wherein the image resolution comprises at least one of a spatial resolution or an intensity resolution.

5. The method of claim 2 wherein the one or more image characteristics comprise ISO speed.

6. The method of claim 1 wherein setting the quantity of SDL pixels within each of the pixel regions to the first number comprises setting the quantity of SDL pixels to the smallest number for which the first image meets a predetermined quality metric.

7. The method of claim 1 further comprising:

exposing the array of SDL pixels to incident light during a second interval;

reading out second pixel values that indicate respective exposure states of the SDL pixels following the second exposure interval;

forming a second image containing second digital values that correspond to respective pixel regions of the plurality of pixel regions, including combining the second pixel values read out from the plurality of SDL pixels within each of the pixel regions to generate a respective one of the second digital values; and

combining the first digital values and the second digital values within an output image.

8. The method of claim 7 further comprising adjusting the setting of the quantity of SDL pixels within each of the pixel regions prior to forming the second image.

9. The method of claim 1 wherein setting the quantity of SDL pixels within each of the pixel regions comprises setting the quantity of SDL pixels based, at least in part, upon light level.

10. The method of claim 1 wherein reading out first pixel values that indicate respective exposure states of the SDL pixels corresponding to the first exposure interval comprises reading out at least a portion of the SDL pixels more than once.

11. The method of claim 1 wherein a first pixel region of the plurality of pixel regions includes one or more SDL pixels that are also included in a second pixel region of the plurality of pixel regions.

12. The method of claim 1 wherein the plurality of pixel regions are non-overlapping.

13. The method of claim 1 wherein combining the first pixel values read out of the plurality of SDL pixels within each of the pixel regions to generate a respective one of the first digital values comprises setting the respective one of the first digital values to a first level if none of the first pixel values read out of the plurality of SDL pixels within the corresponding pixel region exceed a threshold and to a second level if at least one of the first pixel values read out of the plurality of SDL pixels within the corresponding pixel region exceeds the threshold.

14. An image sensor comprising:

an array of sub-diffraction-limit (SDL) pixels; and

readout circuitry to (i) read out first pixel values that indicate respective exposure states of the SDL pixels corresponding to a first exposure interval and (ii) generate, as a first image, a plurality of first digital values that correspond to respective pixel regions, including combining the first pixel values read out from a respective plurality of the SDL pixels that constitute each of the pixel regions to generate a respective one of the first digital values.

15. The image sensor of claim 14 wherein the readout circuitry comprises circuitry to adjust a size of the pixel regions by changing the constituent number of SDL pixels and thereafter generate, as a second image, a plurality of second digital values that correspond respectively to the size-adjusted pixel regions.

16. The image sensor of claim **15** wherein the circuitry to generate, as the second image, the plurality of second digital values that correspond respectively to the size-adjusted pixel regions comprises circuitry to combine the first pixel values read out from the SDL pixels that constitute each of the size-adjusted pixel regions.

17. The image sensor of claim **14** wherein the readout circuitry to readout first pixel values that indicate respective exposure states of the SDL pixels corresponding to a first exposure interval comprises circuitry to read out at least a portion of the SDL pixels more than once.

18. The image sensor of claim **14** wherein a first one of the pixel regions includes one or more SDL pixels that are also included in a second one of the pixel regions.

19. The image sensor of claim **14** wherein the pixel regions are non-overlapping.

20. The image sensor of claim **14** wherein the readout circuitry to combine the first pixel values read out of the plurality of the SDL pixels that constitute each of the pixel regions comprises circuitry to set the respective one of the first digital values to a first level if none of the first pixel values read out of the plurality of SDL pixels that constitute the corresponding pixel region exceed a threshold and to a second level if at least one of the first pixel values read out of the plurality of SDL pixels that constitute the corresponding pixel region exceeds the threshold.

*   *   *   *   *