ASSESSMENT OF IMAGE SENSOR TECHNOLOGY FOR FUTURE NASA MISSIONS

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ABSTRACT

An assessment of solid-state UV/visible image sensor technology for future NASA missions is presented. The paper will attempt to summarize the state of the art in image sensor technology in the United States, Canada, Japan, and Europe. The state of the art and future trends will be compared to a forecast of future NASA needs in scientific image sensors for planetary exploration, earth science, astrophysics, and spacecraft systems such as star trackers and optical communications.

1. INTRODUCTION

The National Aeronautics and Space Administration utilizes a wide variety of image sensors in its manned and unmanned space missions. In 1993, a small study was performed by the Office of Advanced Concepts and Technology to better understand the state of the art in industry for advanced image sensors and to better understand future mission needs and requirements for new technology research, development and insertion. The scope of the study was limited to visible and UV/visible image sensors, and particularly charge-coupled devices (CCDs) and active pixel sensors (APS), with particular attention to remote, scientific sensing applications.

The study was performed by interviewing science investigators, NASA Headquarters personnel, industry technologists, and by visiting numerous companies and laboratories in the US., Canada, and Japan. Additional sources included conferences such as the 1993 SPIE CCDs and Solid-State Optical Sensors III conference held in February 1993 in San Jose, California, the 1993 IEEE Workshop on CCDs and Advanced Image Sensors held in June 1993 in Waterloo, Ontario, Canada, and the 1993 IEEE International Electron Devices Meeting held in December 1993 in Washington DC. Material from previous NASA Workshops were also used, such as the 1991 Astrotech 21 [1] and the 1992 Space Microtechnologies [2] Workshops.

The purpose of this paper is to provide a framework for discussing a possible investment strategy for NASA in the area of scientific sensors for UV/visible imaging. Background material on CCD and APS technology is provided. A short summary of the state of the art in each of the major manufacturers is then reported. User requirements and desires are addressed. A short section on the likely areas of technology push (without NASA investment) is given. Finally, a brief section on a strawman investment strategy for NASA is presented.

2. BACKGROUND

To provide context for description of the state of the art and future technology needs, a short background on CCD and APS technology is presented.

2.1 CHARGE-COUPLED DEVICES (CCDS)

CCD technology has been developed for scientific use since its invention in 1970. The CCD has several advantages over its vidicon-tube and photodiode array predecessors. Photodiode arrays, in the late 1960's, [3,4] used switches to connect individual photodiode elements to a common output line. The high capacitance of the photodiode output lines combined with large switch feedthrough and small photosignals created an opportunity for improved imaging detector arrays. The CCD, which physically transported the photosignal to a common output amplifier solved many of the difficulties associated with the performance of photodiode arrays. The principle of charge transfer using fringing electric fields from adjacent electrodes is inherent in the CCD concept. Charge is transferred from under one electrode to the next, in shift register fashion, by varying the voltages on the overlying MOS electrodes. Compared to the photodiode arrays, uniformity improved through the use of the common output amplifier and noise was greatly reduced with the use of a small floating diffusion

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capacitance and the introduction of correlated double sampling. With the concurrent development of metal-oxide-semiconductor (MOS) technology in the early 1970's for integrated circuit applications, CCD performance continued to improve. NASA Code R (now Code C), recognizing the potential for replacing low-reliability vidicon vacuum tubes with a solid-state imaging device, supported the development of scientific CCDs, while industry developed commercial CCDs for video applications [5]. In the 1980's, the advent of the consumer camcorder helped bootstrap Japanese investment in CCD technology to improve yield, performance and reduce manufacturing costs. Scientific CCD development in the US lost its synergism with commercial CCD development as camcorder CCD manufacturing moved to Asia. Only DoD and NASA support helped maintain a technology base in the US., though electronic imaging, as a replacement for photographic film, has also driven continued development of CCD technology. Today, scientific CCDs represent a market niche for several companies in the US, but Asian interest in producing scientific CCDs grows.

As a first generation solid-state imaging device technology, scientific CCDs have numerous performance advantages over most competing technologies for UV/visible imaging. These include small pixel size, high fill-factor, large format, low read noise and low dark current. A second generation of solid-state image sensors, though, would include on-chip timing and control electronics, signal processing and analog-to-digital conversion, in addition to high performance image acquisition. Due to the limitations discussed below, the CCD may not be a viable candidate for such a second generation imaging technology.

In the 1980's, scientific CCD technology began to significantly diverge from mainstream integrated circuit technology. While both employ MOS structures, complementary MOS (CMOS) has emerged as the dominant technology for implementation of both analog and digital integrated circuits for microprocessors, memory and custom applications (a.k.a. application-specific integrated circuits or ASICs). Thus, the use of CMOS for digital timing and signal processing on the same chip as the CCD requires one of two undesirable compromises. Either the CCD or CMOS structure must be altered to conform to a combined process resulting in lower CCD or CMOS performance, or a significant number of additional fabrication steps must be inserted to allow both structures to be fabricated at penalty of reduced yield and increased manufacturing cost. A second and equally important issue for the integration of CCDs and CMOS is that large area CCDs are inherently highly capacitive devices. To drive such high capacitances at reasonable imaging rates, large current drive capability with associated high power dissipation must be incurred. This is generally undesirable for most applications. Thus, CCDs and CMOS are difficult to integrate for several reasons. (Linear CCDs for consumer applications often utilize on-chip CMOS circuits, and some small CCD area arrays have been integrated with CMOS).

There are additional difficulties with CCD technology that are all traceable to the fundamental principle of operation of a CCD -- charge transfer. In order to maintain high signal fidelity in a CCD image sensor, charge must be physically transported to the output amplifier with nearly perfect charge transfer efficiency (CTE), i.e., no charge can be lost due to traps or spilling en route to the amplifier. For a large number of transfers (e.g. 10,000) the transfer efficiency per transfer must be very high (e.g. 0.999999) so that the net transfer efficiency ($0.999999^{10000} = 0.99$) is reasonable. Thus, CCDs require large clocking voltages (10-15 volts) to enable high CTE, CCD performance degrades with increasing array size unless CTE is increased, CCD performance degrades with increasing readout rate since CTE drops at higher transfer speeds, CCD performance degrades in the presence of trap-inducing radiation (especially protons), CCD performance degrades at low temperatures due to trapping, and CCDs do not allow random access or simple window-of-interest readout operation since all data must pass through the output amplifier or into a dump drain.

Despite these limitations, scientific CCDs have achieved an impressive level of performance. Arrays as large as 2K x 2K are routinely fabricated with 7.5 μm pixels, 50,000 electron full well capacity, CTE greater than 0.999995, room temperature dark current less than 25 pA/cm^2, response non-linearity less than one percent, uniformity less than two percent, sensitivity of 1.0 μV/electron (kept low to maintain linearity) and readout noise of less than 5 electrons r.m.s.

2.2 ACTIVE PIXEL SENSORS (APS)

The need to address the limitations of the CCD have led to a new image sensor technology, that in some sense, is a natural evolution of the original photodiode imaging detector array combined with some CCD concepts. In the active pixel image sensor, active transistors are located within each pixel to amplify and buffer the signal [6]. Charge does not need to be transported across great distances to an output amplifier so that all of the drawbacks of the CCD related to charge transfer are eliminated. Low voltages operation is enabled, performance does not degrade with increasing array size, readout rate is increased, radiation vulnerability is decreased, low temperature performance is enabled, and random access architectures become possible. Furthermore, compatibility with on-chip CMOS timing and control, signal processing and analog-to-digital conversion is generally increased, though for some high performance APS structures, additional fabrication steps are still required.

APS detector arrays have the same general detection characteristics as CCDs. Optical quantum efficiency is similar to the CCD, and techniques used for CCDs such as pinned photodiodes, use of lumogen wavelength-shifting phosphors, and backside thinning for UV enhancement are relevant to APS technology as well. Dark current has similar limitations, though operation in a pinned surface mode has not yet been demonstrated for the APS. However, the APS can be cooled to a much lower temperature than the CCD to fully suppress dark current and not suffer performance degradation due to CTE limitations. Because the APS can be designed for non-destructive readout, multiple sampling may be used to reduce read noise to the sub-electron level as has been demonstrated for CCDs.

There are some technological hurdles still to be crossed by the APS before its performance for scientific applications becomes competitive to the CCD. These include improvement in optical aperture or fill-factor, possibly through the use of microlense technology, reduction of fixed pattern noise due to amplifier-to-amplifier operating characteristics, and reduction in dark current. None of these hurdles is fundamental, and given the relative immaturity of APS technology, it is expected that most will be crossed in a few years. Meanwhile, APS technology is finding its own niche in low cost, less demanding commercial applications such as video phones, machine vision and computer input devices.

2.3 OTHER IMAGE SENSOR TECHNOLOGIES

There are other image sensor technologies that could be considered for scientific remote sensing applications. State-of-the-art photodiode arrays have read noise of the order of 300 e- r.m.s. and charge injection devices (CIDs) also have high read noise, of the order of 200 e- r.m.s. (25 e- r.m.s. after 100x oversampling) [7]. Thus, these technologies are not considered further here. Hybrid devices are often used for infrared focal-plane arrays but not generally for visible wavelengths. Hybrid arrays are also generally limited to small array sizes (under 512 x 512), larger pixel pitches (25 μm), and higher read noise (30 e- r.m.s.). Microchannel plate devices such as the MAMA are under development for UV imaging and hold great promise for low background scientific imaging but are not solid-state imaging devices and were beyond the scope of this study.

3. STATE OF THE ART

In this section, an attempt is made to summarize the state of the art in solid-state imaging devices. It should be understood that any such summary is a simple snapshot in time, and any generalization is always subject to exceptions. The list is as complete as possible at the time of this writing.

3.1 US IMAGE SENSOR MANUFACTURERS

CIDTEC

CIDTEC (Liverpool, NY) produces charge injection device (CID) image sensors. CIDs feature random access capability, non-destructive readout, radiation hardness and high fill-factor. Largest CID array sizes are 512x512. On-chip signal processing circuits have been incorporated to reduce noise. Typical scientific pixel pitch is 28 μm.

EG&G Reticon

Reticon (Sunnyvale, CA) originally produced photodiode arrays (a.k.a. "reticons"). In addition to photodiode arrays, Reticon also fabricates CCDs in various formats. Typical pixel size is 12.5 μm on 4 inch wafers and Reticon has demonstrated arrays sizes as large as 2K x 2K. Reticon has developed a backside thinning capability on a die-by-die basis. Reticon does not generally perform a CCD foundry service, but will design and fabricate custom CCD image sensors, and will consider foundry-type arrangements. Reticon has also developed a specialty in high frame rate image sensors.

IBM

IBM Research Division (Yorktown Heights, NY) produces low volume, large TDI CCD image sensors for IBM document scanners using two poly, four phase technology. CCD production is at IBM in Japan. IBM does not presently provide CCD foundry services and does not have a backside thinning capability.

Kodak

Kodak (Rochester, NY) is likely the largest volume producer of CCDs in the United States. Kodak makes both interline transfer devices as well as full-frame devices with a maximum demonstrated size of 2K x 3K, and more typically 1K x 1K. The interline transfer devices utilize a pinned photodiode structure for low dark current and good blue response. Electronic shuttering and vertical overflow drain (VOD) structures are commonly employed. Kodak does not operate in a foundry mode but will perform custom design of CCDs and has a large R&D group. In full frame devices, the smallest pixel size is approximately 6.8 μm x 6.8 μm, and for interline devices, 6.8 μm x 7.8 μm. Wafer thinning is not presently available from Kodak.

Litton

Litton (formerly Varian) produces GaAs/AlGaAs CCDs for DoD applications. These are generally small arrays (e.g. 100x100) that are radiation hard.

Loral

Loral comprises the former Fairchild (Milipitas, CA) and Ford Aeronutronics (Newport Beach, CA) CCD manufacturers. Loral specializes in high performance, large format CCDs with typical pixel sizes ranging from 7.5 μm to 15 μm. Typically, a triple poly, three phase architecture on 4-inch wafers is used. Loral has demonstrated a 4K x 4K sensor and routinely fabricates 2K x 2K sensors. Loral also serves as a CCD foundry service, fabricating user-defined designs at the wafer lot level, in addition to providing design services. Wafer thinning is not presently available from Loral. Loral has a large DoD business base in infrared and visible CCDs in addition to scientific imaging.

Orbit Semiconductor

Orbit Semiconductor (Sunnyvale, CA) has recently announced a CCD foundry service in addition to their CMOS foundry service. Typical achievable pixel size is 5 μm on 4 inch wafers. Very large format arrays have been produced, up to 8 Mpixels and larger. Orbit will also perform custom CCD design.

Polaroid

Polaroid (Cambridge, MA) performs image sensor R&D for both CCDs and CIDs. Polaroid does not currently sell image sensors externally, but supplies internal customers. Polaroid does not presently perform foundry work and does not have a backside thinning capability.

David Sarnoff Research Center

Sarnoff (Princeton, NJ) is the former RCA Laboratories. Sarnoff performs contract R&D on specialized CCD devices and small volume production of UV/visible and IR CCD arrays. They fabricate multi-poly architectures on 4 inch wafers, and have a wafer-level backside thinning and high temperature, stable, UV enhancement capability. Typical pixel size is 18 μm and they have produced 2 Mpixel image sensors with lateral antiblooming structures and low dark current. They have a growing activity in scientific image sensor development.

Scientific Imaging Technologies

SITe (Beaverton, OR) is the former Tektronix imaging devices group. SITe specializes in frontside and backside thinned, large format scientific CCDs. Typical pixel size is 15-24 μm, with the smallest pixel size presently available being 15 μm. Array sizes as large as 2K x 2K have been demonstrated. Backside thinning, passivation and UV enhancement are also performed.

Texas Instruments

Texas Instruments (Dallas, TX) produces CCDs (fabricated by TI Japan) for industrial and consumer applications. TI performs some custom CCD work but does not offer a foundry capability. Typical design rules are 1.5 μm leading to 9 μm pixel sizes on 5 inch wafers. TI developed the virtual phase image sensor that has led to the use of pinned CCDs and pinned photodiodes for the suppression of dark current but does not presently produce scientific CCDs TI has also developed several active pixel sensors including the floating gate array (FGA) sensor that evolved to the bulk charge modulated device (BCMD).

Westinghouse

Westinghouse (Baltimore, MD) has developed CCDs for DoD applications, including imaging and signal processing, and pioneered the use of correlated double sampling for kTC noise suppression. Westinghouse has developed tin-oxide transparent gate electrodes for high quantum efficiency in all visible wavelengths (e.g. 70% avg. in 400-800 nm band). Westinghouse specializes in TDI imagers (1152 x 64) and performs custom CCD design and fabrication, but does not offer a foundry service.

3.2 OTHER US LABORATORY AND UNIVERSITY EFFORTS

AT&T Bell Laboratories

AT&T Bell Laboratories (Holmdel, NJ) is developing custom CMOS APS image sensors for use by internal customers in low cost commercial applications.

M.I.T. Lincoln Laboratory

Lincoln Laboratory (Lexington, MA), an Air Force Federally Funded R&D Center (FFRDC) and part of the Massachusetts Institute of Technology, has made a significant investment in CCD technology for various DoD programs. Lincoln Laboratory makes large format (up to 1960 x 2560), small pixel (12 μm) CCDs on 4 inch wafers. They have also developed several backside thinning and UV enhancement processes. Lincoln Laboratory does not generally perform CCD foundry service and only performs work for NASA through programs at M.I.T. Lincoln Laboratories has also pioneered ultra-low noise CCDs on high resistivity silicon for low energy x-ray detection [8].

Jet Propulsion Laboratory

Jet Propulsion Laboratory (Pasadena, CA) is a NASA FFRDC and is part of the California Institute of Technology. JPL has developed scientific CCDs through collaboration with industry, and recently has designed a number of high performance scientific CCDs featuring low dark current, low read noise and large format [9]. JPL has significant expertise in the testing and characterization of scientific CCDs. JPL has also developed a backside UV enhancement process using low temperature molecular beam epitaxy. Recently, JPL has been exploring the use of CMOS active pixel image sensors (APS) for highly integrated imaging systems [10].

New Jersey Institute of Technology

The New Jersey Institute of Technology has established a small center specializing in electronic imaging. The center director, Prof. W. Kosonocky, is well known for pioneering CCD development at RCA Laboratories. The center performs design and testing of custom image sensors.

3.3 CANADIAN IMAGE SENSOR ACTIVITIES

DALSA

DALSA (Waterloo, Ontario CANADA) designs and fabricates (via foundries) a number of CCD image sensors for industrial, defense, and scientific applications. DALSA has a standard product line but will also perform custom designs.

DALSA has produced, via foundry, one of the largest CCDs ever manufactured -- 5K x 5K [11]. Typical pixel sizes are 12 μm fabricated on 4 inch wafers.

TRIUMF

TRIUMF (Vancouver, CANADA) is a high energy physics research laboratory and is part of the University of British Columbia. TRIUMF has developed linear GaAs CCDs for fast-in, slow-out data acquisition applications.

3.4 EUROPEAN IMAGE SENSOR MANUFACTURERS

EEV

EEV - English Electric Valve (Chelmsford, Essex ENGLAND) has developed several scientific image sensors. A backside illuminated CCD with 22.5 μm x 22.5 μm pixels (three phase), in a 780 x 1152 format, has been developed for an imaging spectrometer and operates up to 3 MHz readout rate. Backside thinning has been developed both for window-style and full-chip thinning [12]. EEV has also developed thick, high resistivity CCDs for European x-ray astronomy missions.

Philips

Philips (Eindhoven, NETHERLANDS) is a vertically integrated manufacturer of consumer electronics. Philips develops and manufactures CCDs primarily for their internal products. Philips makes sensors for TV and HDTV and uses frontside-illuminated frame transfer devices. Philips has made numerous innovations in CCD structure and design, including an accordion frame transfer architecture, and a T-shaped frontside electrode that allows good blue response through open regions in a frame transfer device [13]. Philips has also recently explored very thin poly-silicon gate devices with metal straps [14].

Thomson

Thomson (St. Egreve, Cedex FRANCE) is a large electronics manufacturer, especially for defense applications. Thomson manufactures both commercial and scientific image sensors. They have fabricated a 2K x 2K, 3-side buttable, frontside-illuminated image sensor with a pinned CCD operation mode (two poly, four phase) using 15 μm x 15 μm pixels, achieving low noise and low dark current [15]. Thomson will perform custom CCD design and fabrication.

VLSI Vision, Ltd.

VLSI Vision (Scotland, UK) produces a low cost CMOS photodiode array with on-chip integrated timing and control electronics and signal processing. The performance of the sensors are consistent with photodiodes and are not presently suitable for most scientific applications.

3.5 JAPANESE IMAGE SENSOR MANUFACTURERS

In general, the focus in Japan is on vertically integrated manufacturing of consumer electronics products. A major recent push has been the development of the 1/4" image sensor for camcorder applications. The small format allows small optics and camera miniaturization. The 250,000 pixel image sensor architecture has been simultaneously developed by several companies. A second thrust is the development of HDTV image sensors for broadcast cameras [16] (consumer HDTV camcorders are not expected to be marketable until at least 1998). HDTV CCDs have a format of 1920 x 1036, resulting in pixel sizes of approximately 7.3 μm x 7.6 μm for 1 inch format (approximately 5 μm for 2/3 inch format) and typically two horizontal readout channels, each operating at 37 Mpixels/sec. Compared to US manufacturers, Japanese design rule are typically much smaller (e.g. 0.6 μm) and the wafer size larger (6 inch). This translates into smaller pixels, larger formats, and lower manufacturing costs. Typical TV-format CCDs, including color filters and microlenses, cost approximately 1000 Yen to manufacture, or about US $10 each. Sony and Matsushita, the largest volume producers, are also considered the manufacturers of the highest performance CCDs. There is no CCD foundry service available in Japan and only a few companies indicate an interest in scientific CCD technology.

Canon

Canon (Hiratsuka-shi, JAPAN) makes cameras, fax machines, copying machines, etc. Canon has developed a bipolar-based active pixel sensor technology known as BASIS for base-stored image sensor [17]. This bipolar device is readily compatible with bi-CMOS integrated circuit manufacturing for the incorporation of on-chip timing, control and signal processing circuits and since no photogate is required, has good blue response and overall good quantum efficiency. The BASIS device has been employed in area and linear sensors for numerous applications such as auto-focus. Canon has demonstrated a 1.3 Mpixel image sensor using the BASIS device, but do not feel the device will be competitive to CCDs for either scientific or HDTV type of applications since it is subject to random reset noise.

Hamamatsu

Hamamatsu (Hamamatsu City, JAPAN) produces scientific optoelectronic devices. Hamamatsu recently reported the investigation of backside illuminated CCDs optimization using several approaches including deposition of SiC, lumogen and implantation [18]. Hamamatsu has also been investigating linear CMOS APS arrays [19].

Hitachi

Hitachi (Kokubunji, JAPAN) makes interline CCD image sensors and until recently was in a catch-up mode to its competitors. However, Hitachi is developing state-of-the-art sensors and recently introduced a new interline CCD readout scheme called punchthrough readout that improves optical fill factor and reduces smear [20]. The 2/3" HDTV format sensor has 5 μm x 5.2 μm pixels in a 1920 x 1035 array size and uses a pinned photodiode for good optical response.

Matsushita

Matsushita Electronics Corporation (Kyoto, JAPAN) produces consumer electronics under the National and Panasonic labels, and once co-owned by Philips and Matsushita Electronics Industries. It is no longer co-owned by Philips. Matsushita pioneered the microlens technology [21]. Matsushita is second only to Sony in CCD production volume. Matsushita has developed a 1" FIT 1300 x 1000 element HDTV CCD image sensor.

Mitsubishi

Mitsubishi (Itami, Hyogo JAPAN) has focused on developing very large format (1K x 1K) infrared charge sweep devices (CSDs) using the PtSi Schottky barrier structure. The CSD is a charge transfer device that is similar to a CCD but is clocked differently to "sweep" charge down the vertical register into the horizontal register. Mitsubishi is not presently investigating visible CSDs, though for a short period, they investigated HDTV sensors.

NEC

NEC - Nippon Electric Corporation (Sagamihara, Kanagawa JAPAN) has made several important innovations in CCD technology. These include the first HDTV CCD, the invention of the vertical overflow drain (simultaneously with Toshiba), the development of the microlens in 1983, and the pinned photodiode structure for interline CCD architectures. NEC makes a wide variety of advanced CCDs for TV [22] and HDTV [23] applications. NEC is also developing several scientific CCD image sensors including linear arrays for earth remote sensing, star tracker sensors, and a UV sensor employing a down converting phosphor. NEC does not perform a foundry service but would consider the design and fabrication of custom sensors for scientific applications.

NHK

NHK (Setagaya-ku, Tokyo JAPAN) is a sort of national television technology research laboratory in Japan. NHK performs both in-house R&D and supports industry through contracts. NHK sponsors R&D on both solid-state image sensors as well as continued development of tube technology. The super-HARP tube, for example has extremely high sensitivity and excellent blue/UV response due to its avalanche Se detector structure. NHK has developed, with industry, the amplified MOS image (AMI) sensor APS [24]. This device is essentially a photodiode with a unit cell source follower, and is inherently CMOS compatible. Excellent imaging results have been reported with small pixel devices (7.2 μm x 5.6 μm) and large formats (250 kpixel).

Olympus

Olympus (Tatsuno, Nagano JAPAN) makes scientific instruments such as endoscopes, microscopes and cameras. Olympus Semiconductor Technology Center has developed several active pixel image sensors including the static induction transistor (SIT) image sensor, the AMI sensor, and most recently the charge modulation device (CMD) image sensor [25]. The CMD image sensor has been demonstrated in an 2/3" 2 Mpixel HDTV format with 5 μm pixels, and dissipates 10x less power than its CCD counterparts. For video applications, the CMD has higher fixed pattern noise than CCDs that limited its marketability. For scientific applications, the CMD offers non-destructive readout capability as well as the potential for random access.

Sharp

Sharp has an aggressive CCD program but the details of the activity have not been ascertained at the time of writing.

Sony

Sony (Atsugi, JAPAN) is well-known for its consumer electronics products. Their major emphasis is on remaining the number one supplier of CCDs in the world. Sony currently produces approximately 5,000,000 CCDs per year and has made 27 million CCDs to date. The focus in CCD R&D is higher sensitivity, higher resolution, and smaller image sensor size, such as the 1/4" TV-format CCD. Sony does not make any scientific CCD products. Typical CCDs use a triple poly, three phase interline transfer CCD architecture with pinned photodiodes. For example, a 380 kpixel 1/2-inch format progressive scan image sensor was demonstrated with 8.4 μm x 9.8 μm pixels [26].

Toshiba

Toshiba (Kawasaki, Japan) makes numerous electronics products. Toshiba has been investigating the use of amorphous silicon overlayers above a CCD for 100% fill factor and blue response improvement [27]. The major difficulty with the approach is the lag and reset noise (e.g. 100 e-) associated with the structure, though recent improvement in both has been reported. While pixel sizes of approximately 12 μm have been demonstrated, the target pixel size is 5 μm for 1/4" optical formats.

3.6 OTHER ASIAN IMAGE SENSOR MANUFACTURERS

Significant advancement is technological capability in CCDs is occurring in both Taiwan and Korea. Camcorder manufacturers in these countries do not want to rely on imports of high performance CCD image sensors from Japan, since the highest performance sensors are not made available to competing camcorder manufacturers. At the time of writing, the only specific information obtained in the course of this study was from Goldstar.

Goldstar

Goldstar (Seoul, KOREA) is a vertically integrated manufacturer of consumer electronics. Goldstar has a crash program in the development of camcorder CCDs and linear CCDs for fax machines and other scanning applications. The advancement is rapid, but not yet at the level of Japanese competitors. Monochrome image sensors for monochrome camcorders and other applications have been developed, with color sensors anticipated in the near future. The emphasis is on consumer TV products and there is no activity in scientific sensors at this time.

3.7 SUMMARY

Several US manufacturers have developed a niche market in the implementation of scientific image sensors. While the technical advantage in CCD manufacturing resides in Japan, the focus in Japan on consumer electronics has precluded Japanese development of large area or backside-illuminated CCD structures. It is possible that this will change in the next few years, since development of spaceborne scientific image sensors is regarded as a non-profitable but prestigious activity. Unfortunately for the scientific community, those companies around the globe that have developed an aggressive technical base in integrated circuit manufacturing are motivated by high volume commercial markets, and are not pursuing scientific applications of the technology, while those manufacturers pursuing low volume scientific markets are unable to make the large capital investment demanded of an aggressive technical program.

A table summarizing the approximate state of the art in various companies is shown below in Table 1. It should be noted that the numbers chosen for this table were selected subjectively and represent a combination of truly typical numbers and some high end numbers. Also, some numbers reflect R&D values whereas others represent production values. This table should be viewed to obtain a general picture of capabilities across the board and not the capabilities of specific manufacturers per se.

TABLE 1.

MANUFACTURER	DESIGN RULE (μm)	TYPICAL PIXEL SIZE (μm)	TYPICAL ARRAY SIZE	WAFER SIZE (inches)	REMARKS
United States					
AT&T	0.9	20.0	25 Kpixel	6	CMOS APS R&D
CIDTEC		28.0	260 Kpixel		CID sensor
IBM	2.0	15	3072x64	5	Internal
Kodak	1.2	6.8	1 Mpixel	4	
Loral		7.5-15.0	4 Mpixel	4	Full foundry service
MIT LL	2.0	12.0-27.0	1 Mpixel	4	Backside illuminated, x-ray
Orbit	1.2	5.0	1 Mpixel	4	Full foundry service
Polaroid	1.2	7.0	1 Mpixel	4	Internal
Reticon	3.0	12.5	1 Mpixel	4	Backside illuminated
Sarnoff	2.0	18.0	2 Mpixel	4	Backside illuminated
SITe	2.0	15.0	1 Mpixel	4	Backside illuminated
Texas Instruments	1.5	9.0	250 Kpixel	5	Commercial focus
Westinghouse	1.1	8.0-12.0	1152x64	4	Transparent electrodes
Canada					
DALSA		12.0	1 Mpixel		Use foundry
Asia					
Canon	1.2	13.5	1.3 Mpixel		BASIS APS
Hitachi		5.0	2 Mpixel		Commercial
Matsushita					Commercial
Mitsubishi					IR CSD device
NEC	0.6	5.0-7.0	2 Mpixel	6	Commercial
Olympus	0.8	5.0	2 Mpixel	4	CMD APS
Sony		8.0	380 Kpixel		Commercial
Toshiba	0.6	12.0	380 Kpixel		Stacked structure
Europe					
EEV		22.5	1 Mpixel		Backside illuminated
Philips			2 Mpixel		Commercial
Thomson	1.5	15.0	4 Mpixel		Backside illuminated

4. USER REQUIREMENTS

Scientific image sensors are used in a number of applications. These include laboratory spectroscopy and imaging for chemical, biological, medical and engineering analysis. Compared to commercial sensors that typically desire responsiveness similar to that of the human eye, scientific image sensors tend to require response anywhere and/or everywhere from 1 Å to 1 μm. For space applications, CCDs are used in both ground-based astronomy and in spaceborne instrumentation. Ground based astronomy requirements are similar to spaceborne astronomy requirements, and ground-based astronomy is generally supported by the National Science Foundation, though some ground-based astronomy is supported by NASA such as the TOPS program. This study focused on the needs of spaceborne remote sensing though many common requirements exist among all scientific applications.

Spaceborne remote sensing includes earth observing instruments, astrophysics instruments, and planetary instruments. Spacecraft systems also require remote sensing image sensors for guidance and navigation (star trackers) and for future optical communications systems.

4.1 GENERAL REQUIREMENTS

Spaceborne image sensor systems share many common requirements. Since the typical objective of the mission is to perform the best possible measurement of a photon flux rate, requirements include high quantum efficiency, stable and calibratable characteristics, excellent readout signal fidelity, low crosstalk, low readout noise, low dark current, and high optical aperture or fill-factor. In addition, there is an increasing desire to miniaturize remote sensing systems to reduce launch mass and consequently mission cost. Thus, while the optical system is expected to become the limiting factor for miniaturization even through the use of lightweight optics, binary optics and other techniques, there is an impetus to reduce the sensor system electronics mass. A major source of mass is the power supplies including solar panels, batteries, magnetics and power conditioning circuits. The sensor electronics system includes the power supplies, digital timing and control electronics, drive electronics to supply the clock signals to the CCD, signal chain electronics to condition the analog output signal using filtering and correlated double sampling, analog-to-digital converter circuits, and spacecraft interface electronics. Miniaturization and simplification of these electronics has high leverage for reducing mission mass, volume and power. Sensor development programs to date have concentrated on improvement of detector array performance, and have largely ignored the impact of the sensor on the total system performance. Future development efforts must begin to place greater emphasis on total system optimization.

4.2 EARTH OBSERVING INSTRUMENTS

Earth observing instruments tend to be spectrometer-based systems rather than conventional imaging systems. Pushbroom systems typically require linear or TDI image sensors with narrow pixel pitch, low crosstalk and high readout speed. Imaging spectrometers require 2D image sensors with high readout rates. Since spectrometers disperse optical illumination from a single spatial point across many pixels, or filter out all but a narrow wavelength band, photonic signals tend to be weak and easily overwhelmed by readout noise -- especially at high readout rates. Extended wavelength performance in a monolithic sensor is also desired. Most spectroscopic systems require photonic signal acquisition from the blue through to the infrared.

4.3 PLANETARY INSTRUMENTS

Planetary instruments include exploratory missions such as Voyager, Galileo and Cassini, lander missions such as MESUR, and near-earth rendezvous missions for asteroid or comet studies. These instruments often carry conventional imaging systems, and more recently are also carrying spectrometry systems as well. Medium-sized formats (e.g. 1K x 1K) are utilized as a compromise between imaging science and downlink data rates. High dynamic range is often desired, but dynamic range (number of encoded bits) is often limited by data capacity. Increased use of image compression will likely lead to a desire for larger formats with electronic windowing. Radiation hardness is required for long duration missions, and especially for missions to the gas giants Jupiter and Saturn. Low dark current reduces sensor cooling requirements. Electronic shuttering can lead to reduced mass and increased reliability by eliminating shutter mechanisms. For some applications, such as a Mars lander, on-chip color filters can be used to eliminate a filter wheel -- another mechanical assembly. Spectrometry systems have requirements similar to that of those in earth observing instruments. Fly-bys tend to require relatively rapid readout rates to avoid motion-induced image blurring perhaps with some sort of interline or frame transfer. Surface exploration also requires cameras for landers and rovers. Highly miniaturized systems are desired for these applications.

4.4 ASTROPHYSICS INSTRUMENTS

Astrophysics instruments, such as the Wide-field/Planetary Camera on the Hubble Space Telescope, tend to demand the highest dynamic range with the lowest possible (sub-electron) read noise. Large formats (e.g. 16 Mpixels) and extremely large formats (e.g. 100 Mpixels) with small pixels (e.g. 5-10 μm) are desired. Astrophysics applications also includes spectroscopic instruments. One major differentiation between spaceborne telescopes and ground-based telescopes is the opacity of the atmosphere in the ultraviolet. Thus, ultraviolet response in spaceborne telescopes is of great interest and improving the UV response of CCDs has been an area of intense activity. Backside illuminated CCDs, offering high UV sensitivity, 100% fill-factor, and high intrapixel uniformity are preferred over frontside illuminated devices. Interferometers and other instruments also require metrically precise focal-plane arrays with well understood intrapixel response.

4.5 SPACECRAFT TECHNOLOGY

Spacecraft systems require image sensor technology approaching scientific performance for both guidance and navigation and for optical communications. Future integrated spacecraft systems may utilize the same sensor for guidance and navigation, optical communications and science imaging.

Guidance And Navigation

Star trackers acquire star patterns to determine spacecraft attitude, and to help point spaceborne telescope systems. The star tracker must be able to acquire both bright and faint stars in the same field of view and so must have a large dynamic range. Since centroiding of a Gaussian photon spatial distribution is needed for sub-pixel resolution, star trackers also require well-understood intra-pixel response as well as low crosstalk. Star tracker array sizes rival those of scientific sensors since for fine guidance, the field of view must be quite large to ensure the presence of an adequate number of stars. Like the scientific sensor system, star tracker subsystems need to be miniaturized to reduce spacecraft mass, volume and power. Unlike the science sensor, windowed readout may be utilized to reduce the total data volume from the star tracker, since usually only a few stars need to be tracked following the initial acquisition of the star pattern. Non-destructive readout with selective reset to allow variable integration times for each star would help improve overall system performance.

Optical Communications

Future optical communications systems promise higher bandwidth communication between Earth and remote sensing spacecraft. Like a star tracker, the optical communications sensor must lock on to a beacon signal that appears as a point source. Modulation of the beacon signal may be used to transmit information from Earth to the spacecraft. High accuracy pointing of the spacecraft transmitter is also required to allow optimized signal return from the spacecraft. Unlike science sensors, optical communications sensors require shorter integration periods and faster readout rates. Array sizes are likely to be smaller than scientific sensor requirements.

5. TECHNOLOGY PUSH FROM INDUSTRY

Industry is pushing image sensor technology in a number of ways that will benefit scientific remote sensing. There were five major pushes identified. These are TV-format camcorder CCDs, broadcast camera HDTV CCDs, electronic photography, low cost CMOS image sensors, and scientific CCDs.

In the commercial world, CCDs are being produced in very high volumes at low cost in vertically integrated manufacturers of consumer electronics, especially camcorders. Some of these companies also sell their CCDs to other consumer electronics manufacturers as well. The emphasis is on reducing sensor cost (although that is already quite low), increasing responsivity through the use of microlenses, pinned photodiodes, transparent electrodes and smaller interline CCD channels (camcorders are notoriously poor under typical home indoor lighting conditions), and reducing image sensor size to reduce camcorder optics size without compromising optical performance. These are the focal points because this is what the manufacturers believe will lead to both increased sales volume and increased market share. Nearly all this activity is taking place in Asia, with a strong push in Korea and Taiwan to catch up to Japan. The only significant US activity for consumer electronics is at Texas Instruments whose CCD manufacturing takes place at TI Japan. Philips is working hard to retain its edge in Europe in consumer electronics.

In the course of the study, it was found that no major manufacturer of area sensor CCDs in the world had activity in the development of highly integrated sensors including on-chip ADC. One well-respected manufacturer stated that they thought that by not integrating on-chip ADC they helped enable their OEM customers to differentiate their products though the use of add-on ICs for various signal processing functions. In general though, they all felt that on-chip ADC would be developed, but for now the focus was on image sensor performance as described above.

A related technology is the concurrent development of both electromechanical and electronic image stabilization systems for hand held camcorders. Such technology may find use in the stabilization of scientific image sensors on moving platforms.

A second major push is the development of HDTV CCD image sensors. These sensors require much higher performance than their TV counterparts. At 2 Mpixels, HDTV sensors rival the typical size of scientific image sensors, yet have readout rates that are typically 1000 times faster with only a factor of perhaps 5 increase in noise. It is quite likely that slow scan operation of the HDTV sensors would yield very high performance, but this experiment has yet to be carried out.

A third push is in electronic photography. Most major film/camera manufacturers (e.g. Kodak, Polaroid, Olympus, Canon, Ricoh, etc.) have some activity in the area of solid state image sensors. Electronic photography is the closest commercial application to scientific image sensors, since large format, high performance, low dark current and other characteristics are required. Furthermore, in the case of hand-held portable cameras, highly integrated electronics and packaging, low power dissipation and on-board data compression are desired. In the US, Kodak has made a major investment in this area using CCD technology and CMOS ASICs for color signal processing and dead pixel correction, and Polaroid has maintained a strong R&D base. Electronic motion picture photography, a goal more challenging than HDTV, is a possible future growth area. Closer coupling between scientific applications and electronic photography technology development is warranted.

A fourth and rapidly developing technology push is in the area of low cost CMOS commercial sensors for consumer applications. CMOS is attractive for two major reasons. First, CMOS is inherently compatible with on-chip CMOS timing, control, drive and signal processing circuits allowing for the implementation of highly integrated imaging systems. Second, the cost of a CMOS image sensor with on-chip electronics is much less than a CCD image sensor without on-chip electronics. For low volume production (e.g. using a CCD foundry), the cost of a 6 inch CMOS wafer is comparable to the cost of a 4 inch CCD wafer, and the 6 inch wafer has three times the available device area. For example, the cost of producing a lot of 20 CMOS wafers 0.8 μm design rule) is approximately $15K. VLSI Vision Ltd. in Scotland is marketing an inexpensive CMOS image sensor with on-chip timing and control electronics (though of somewhat low image quality according to several persons familiar with the camera.) JPL has developed a CMOS active pixel image sensor with high performance (presently 40 e- read noise, quantum efficiency comparable to IL-CCDs) that has random access capability and is TTL compatible. NHK has been developing the AMI sensor that is essentially a photodiode and source-follower per pixel for several years with high signal-to-noise ratio (but higher noise than the JPL sensor). AT&T is developing CMOS image sensors for video phone applications. Additional applications that are presently under investigation include home surveillance, computer input devices, automotive imagers, and machine vision for parts inspection. These sensors, while not presently having the performance of CCDs in either pixel size or absolute noise, are not fundamentally limited from achieving higher performance and are establishing a market niche that will allow their continued development. Furthermore, since CMOS is a widely accessible technology, especially compared to CCDs, it is anticipated that additional rapid development in CMOS image sensors will occur in the next few years.

The fifth technology push is in the area of scientific image sensors for scientific and clinical applications. There is substantial interest and investment from the scientific community to support small companies to develop scientific image sensors (e.g. SITe and Reticon). The use of scientific sensor technology for biomedical applications (e.g. digital x-ray mammography) is also expanding. Laboratory scientific sensors will continue to develop without investment from NASA and the activity should be considered a synergistic technology push from industry.

6. POSSIBLE TECHNOLOGY INVESTMENT STRATEGY FOR NASA

NASA has had a philosophical change in its technology investment strategy in the past few years. Several years ago, NASA preferred to invest in technologies that were not being concurrently developed by industry for either commercial or

DoD needs, unless a strong potential was identified for leveraging the investment to develop NASA-specific spin-offs. Instead, NASA preferred to invest in those technologies that were so NASA-specific and mission-critical that industry would not develop the technology without direct NASA intervention and investment. In the past few years, there has been a major paradigm shift towards developing dual-use technology that would meet certain NASA needs yet also would have a clear application in the commercial marketplace, either for civilian use (preferred) or defense needs. This places funding for NASA-specific technologies (e.g. 0.1K bolometer sensor readout electronics or solar-blind UV detectors) in a degree of jeopardy. The strategy for NASA investment must include a balance between developing technical solutions to well-understood sensor deficiencies in meeting requirements for planned future missions, and developing new technologies that improve scientific return or enable new science to be performed. A successful strategy must develop technologies that are germane to a broad number of anticipated science missions (e.g. reduced readout noise in CCDs) yet be highly important to one or two near term planned missions. Support for scientific remote sensing sensor technology development presently comes from both the Office of Advanced Concepts and Technology (Code C) and the Office of Space Science (Code S). A strawman list of possible investment areas that meet these criteria are described below.

6.1 VERY HIGH QUANTUM EFFICIENCY SENSORS

Very high quantum efficiency is desired in a broad spectral range. This implies both non-obscuration of the photoactive region (e.g. frontside polysilicon electrodes) and high fill-factor. Blue and ultraviolet radiation is particularly susceptible to absorption in thin, "dead" layers. In the area of ultraviolet solid-state detectors, two approaches can be considered. Such technology has application to an advanced camera for the Hubble Space Telescope, numerous ground-based astronomy facilities, small explorer missions, space-based spectroscopy, and advanced astrophysics missions for astrometry. Such a technology would be commercially important for laboratory imaging and spectroscopy applications. High quantum efficiency broadband visible sensors are also desired.

Backside illumination technology

Acceleration of the development of backside illumination technology for large format, small pixel size, high performance image sensors is a candidate area for increased NASA support. At the present time, backside illumination technology is being developed at a number of manufacturers and research laboratories. However, a truly satisfactory backside thinning, passivation, UV enhancement and packaging technology has yet to be developed. The National Science Foundation has supported a thinning effort at the University of Arizona that was intended to become a national facility for scientific CCD thinning, but there is a need for either greater support or concurrent development elsewhere. There is presently a mismatch between those companies making large format, small pixel, high performance image sensors and those companies offering wafer thinning and UV enhancement. This mismatch has left a large number of science investigators and technologists frustrated. It should be noted that backside illumination technology is applicable to active pixel image sensors, and reduces the drawback of reduced frontside illumination fill factor. The same challenges exist for either CCD or APS application.

Solar-blind detectors

For many applications, it is difficult to filter out visible illumination to the level required for sensitive ultraviolet measurements. The development of sensors in wider bandgap materials (e.g. GaN, SiC, diamond) that are intrinsically insensitive to visible radiation ("solar-blind") would make the process of eliminating any visible background greatly simplified. For example, this is one of the major advantages of the photocathode used in microchannel plate (MCP) detectors for UV remote sensing. A solid-state device that was solar-blind yet had the performance of a CCD would likely eclipse MCP-type detectors. Only limited activity in this area is presently supported, mostly by DoD basic research (6-1) grants. The application of the active pixel sensor (APS) concept to solar-blind materials can be considered a reasonable match of material properties and device performance. Fabrication of CCDs with high performance in these materials is not likely due to anticipated material limitations, such as charge trapping, that would severely limit CTE.

Frontside illumination technology

Improvement of quantum efficiency in frontside illuminated structures is also important for many applications, especially since frontside illumination devices are simpler to manufacture. Candidate technologies for improving the quantum efficiency of frontside illuminated structures include space-compatible microlense or binary optics technology, transparent electrode materials such as tin-oxides, overlayer technology such as a-Si for 100% fill factor or Se for avalanche multiplication, and improved wavelength conversion phosphor structures such as an integrated Wood's filter and lumogen combination.

6.2 EXTREMELY LARGE FORMAT IMAGE SENSORS

Extremely large format image sensors are desired for telescope applications. Such sensors will likely entail a combination of wafer-scale integration of the image sensor, and mosaics of these sensors. For CCDs, such large formats introduce issues of charge-transfer efficiency, radiation hardness, reliability, and especially readout rate. For example, a sensor with a 10K x 10K array of detector elements (10^8 elements), read out at the current state-of-the-art readout rate for scientific sensors of 50 Kpixels per second, would take 2000 seconds, or over a half hour to read out. Such a long readout time introduces dark current concerns as well as those for telescope time. A combination of multiport readout and higher readout rates (with the preservation of low noise) is needed. Active pixel sensors may be more amenable to such large formats since they don't suffer from charge-transfer efficiency limitations, and readout rates can be significantly higher. Such extremely large formats may have application to commercial electronic photography and space surveillance.

6.3 HIGHLY INTEGRATED SCIENTIFIC IMAGING SENSORS

Smaller payloads require smaller imaging instruments. These instruments include camera systems on Discovery-class missions, such as comet and asteroid rendezvous, surface cameras for landers and rovers, as well as deep space missions such as the Pluto Fast Flyby. This will require highly integrated instruments for multi-wavelength band imaging. Highly integrated scientific image sensors will enable realization of such systems. The scientific image sensors should have a full digital interface - digital input signals for sensor control and digitized sensor output. This will necessitate integration of on-chip timing and control circuits, digital interface circuits, on-chip analog-to-digital converters (ADC), and a high performance image sensor. Either CMOS-CCD integration is indicated, or development of active pixel sensor technologies with scientific performance. Such sensors are also important for advanced guidance and navigation systems and for optical communications. High levels of instrument integration will also lead to multi-wavelength band focal-planes, so that packaging technologies that address issues of operating temperature differences and other mismatches are also required. There is enormous commercial application of this technology for consumer applications such as computer input, video phone, intelligent vehicle systems and home surveillance. Other commercial applications include machine vision for inspection and assembly, biomedical imaging, and security systems. There are a number of defense applications as well.

6.4 PHOTON-COUNTING SENSORS

The need for sensors that can discriminate individual photons is highly desired for many advanced astrophysics applications. This requires the reduction of read noise in integrating detector arrays such as CCDs to the sub-electron level (e.g. 0.1 e- rms) or development of digital image sensors that integrate in the digital domain and are sensitive to individual photon events. Such a sensor system could commercially replace MCP and avalanche photodiode arrays in a number of laboratory instruments.

7. SUMMARY

This paper has attempted to summarize the state of the art of solid-state image sensors for UV/visible imaging. There is enormous activity around the world in the area of solid-state image sensors driven primarily by consumer electronics products such as camcorders. Scientific image sensors represent a small niche market for a handful of manufacturers. While the most advanced CCD technologies are being developed in Japan, the scientific image sensor market is dominated by US manufacturers using somewhat older semiconductor technologies and manufacturing techniques. This market dominance by the US may change as Asian manufacturers look to scientific sensors as a prestige industry. Investment by NASA in image sensor R&D may help maintain the US lead in this area, as well as meet unfulfilled requirements for future NASA missions. Four major areas suggested for investment include backside illumination technology, extremely large format image sensors, highly integrated scientific image sensors, and photon-counting sensors.

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