Study on High Speed Imaging Technology for the Microgravity Containerless Processing Facility

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Glossary

A/D	analog-to-digital converter
APS	active pixel sensor
CCD	charge-coupled device
CTE	charge-transfer efficiciency
f/s	frame per second
GaAs	gallium arsenide
GHz	billion per second
Gp/s	billion pixels per second
HDTV	high-definition television
InGaAs	indium gallium arsenide
Mbytes	million bytes
MCPF	Microgravity Containerless Processing Facility
MHz	million per second
msec	thousandth seconds
NIR	near infrared (0.75 - 1.1 microns)
SWIR	short wavelength infrared (1-3 microns)

INTRODUCTION

This report summarizes a small study performed for Dr. Loren Lemmerman and Dr. Nabil Elgabalawi on an imaging system for the Microgravity Containerless Processing Facility (MCPF). The problem studied concerns high speed imaging of hot materials being processed in a microgravity environment in space (e.g. Space Station Freedom). In this system, the materials are at a temperature between 1000^{o}C and 2500^{o}C. The imaging requirements are for two scenarios. First, high resolution imaging (e.g. 1024x1024 pixels) at 500-1000 frames per second is to be considered for drop dynamics. Second, very high speed imaging at 1,000,000 frames per second but lower resolution, e.g. 64x64 pixels is also to be considered. Resolution of 8 bits or better is desired. The study scope includes analysis of the imaging problem, assessment of the state of art, and suggestions for implementation approaches.

Table 1. Summary of Requirements

REQUIREMENTS	Scenario 1 High Resolution	Scenario 2 Very High Speed
Format	1024x1024	64x64
Conversion	8 bits	8 bits
Frame Rate	1,000 f/s	1,000,000 f/s
Data Rate	1 Gp/s	4 Gp/s
Number of Frames	100	1000
Total Imaging Time	100 msec	1 msec
Data Volume	100 Mbytes	4 Mbytes

ANALYSIS OF THE IMAGING PROBLEM

The assumed imaging configuration is shown below:

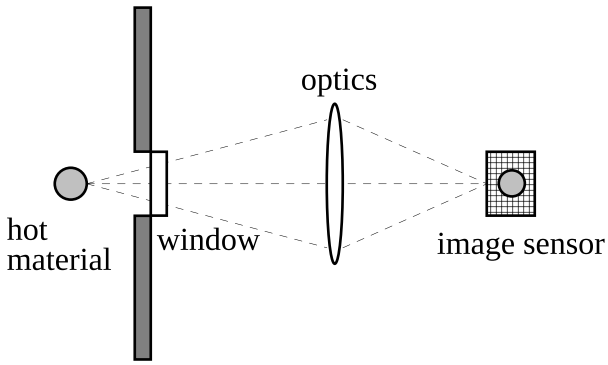

Fig. 1. Imaging configuration

The hot material emits visible and infrared photons in accordance with Planck's blackbody equation. The spectral radiance of the hot material is given by:

$$n_\lambda = \frac{2\varepsilon c}{\lambda^4 (e^{hc/\lambda kT} - 1)} \quad \text{(in photons/sec/sr/m}^2\text{/m)} \qquad \text{Eq. 1.}$$

where λ = wavelength (meters)
c = speed of light (3×10^8 m/sec)
h = Planck's' constant (6.6×10^{-34} J-sec)
k = Boltzmann's constant (1.38×10^{-23} J/^{o}K)
T = temperature (K)
ε = emissivity of the material

The photons are collected by the optics and focused onto the image sensor pixels. If the optics f-number is F, the optics transmission τ, and the pixel area A, the photon flux onto a particular pixel is:

$$N_\lambda = \frac{\pi}{4F^2} A\tau \cdot n_\lambda \quad \text{(in photons/sec/m)} \qquad \text{Eq. 2.}$$

A plot of this function is shown below for various blackbody temperatures, assuming unity emissivity, F/1 optics, and a 50x50 micron pixel.

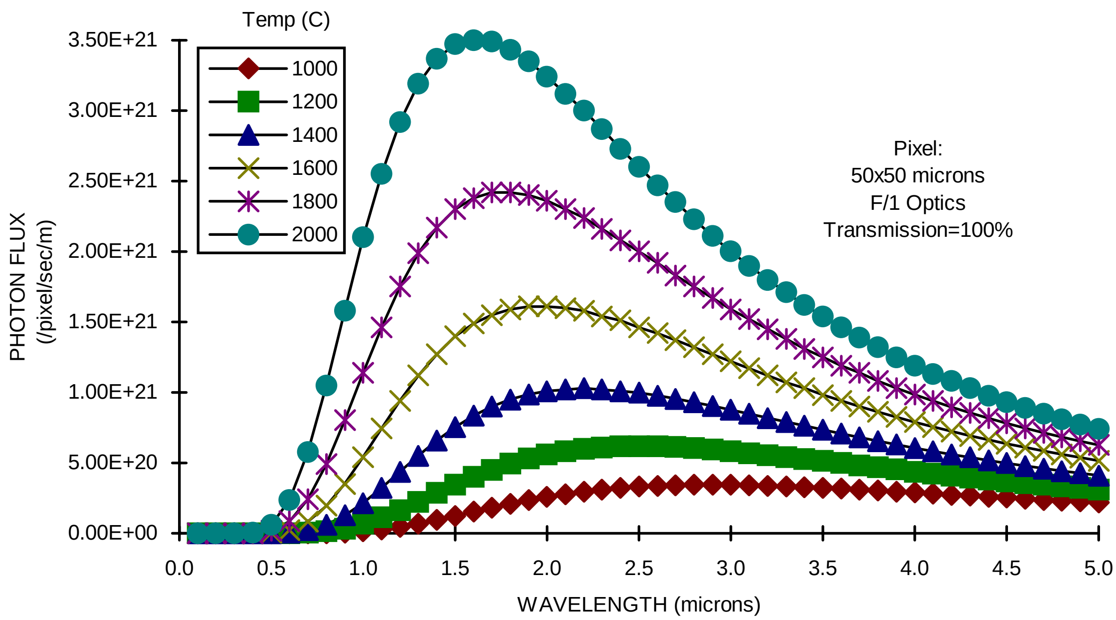

Fig. 2. Blackbody curves for some temperatures of interest.

This plot demonstrates that the photon flux curve peaks in the infrared for most of the temperatures of interest, and on the scale indicated, it appears that for this application one would utilize an infrared detector. However, expanding the region of the curve that lies in the visible/NIR spectrum (under 1.0 microns) yields:

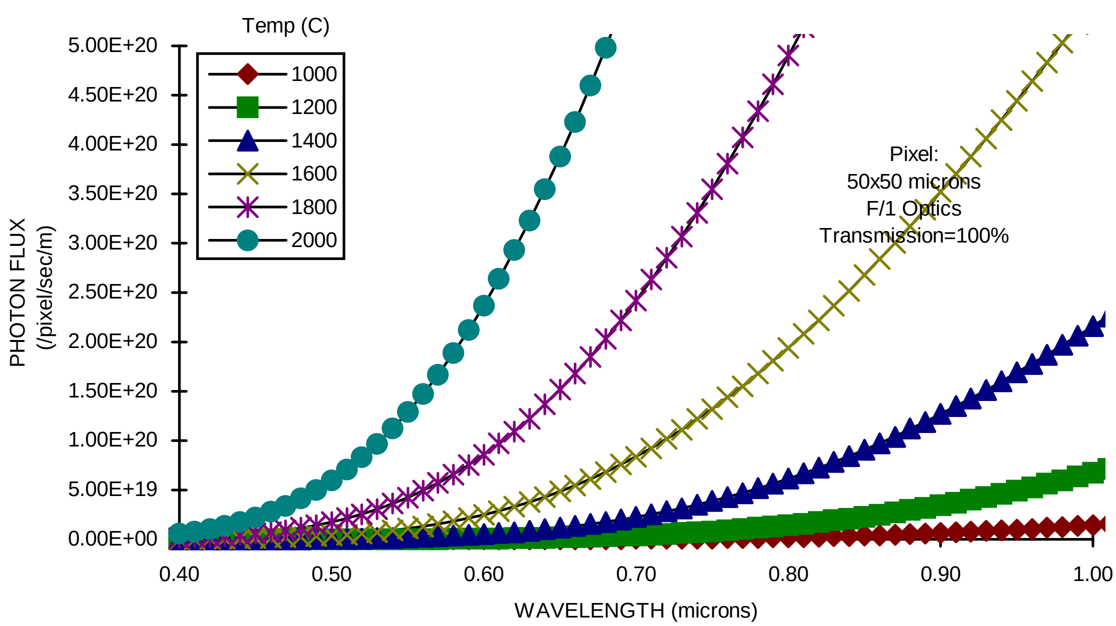

Fig. 3. Expanded visible/NIR view of blackbody curves.

This indicates that there is still a substantial number of photons in the visible/NIR. (Intuitively, we know that hot bodies glow red or orange).

For an imaging system, one is interested in the number of photons that are incident on a detector, integrated over the spectral range of the photodetector. In the detectors of interest in this study, the lower limit of the integration is taken to be 0.4 microns. The actual value is of little consequence since the number of photons below this range is comparatively limited. The upper limit is taken to be the cutoff wavelength of the detector material. For silicon, this cutoff is approximately 1.1 microns, and for GaAs, it is approximately 0.9 microns. Thus, one determines the area under the curve in Fig. 3 between 0.4 microns and the cutoff wavelength, for a given blackbody temperature.

Mathematically, the total flux of photons incident on the pixel is given by:

$$\Phi = \int_{\lambda_1}^{\lambda_2} N_\lambda \, d\lambda \quad \text{(in photons/sec)} \qquad \text{Eq. 3.}$$

where λ_1 = lower wavelength range

λ_2 = upper wavelength range (detector cutoff)

A plot of this function for various temperatures is shown below, with the photon flux integrated over one microsecond, corresponding to imaging at 1,000,000 frames/second.

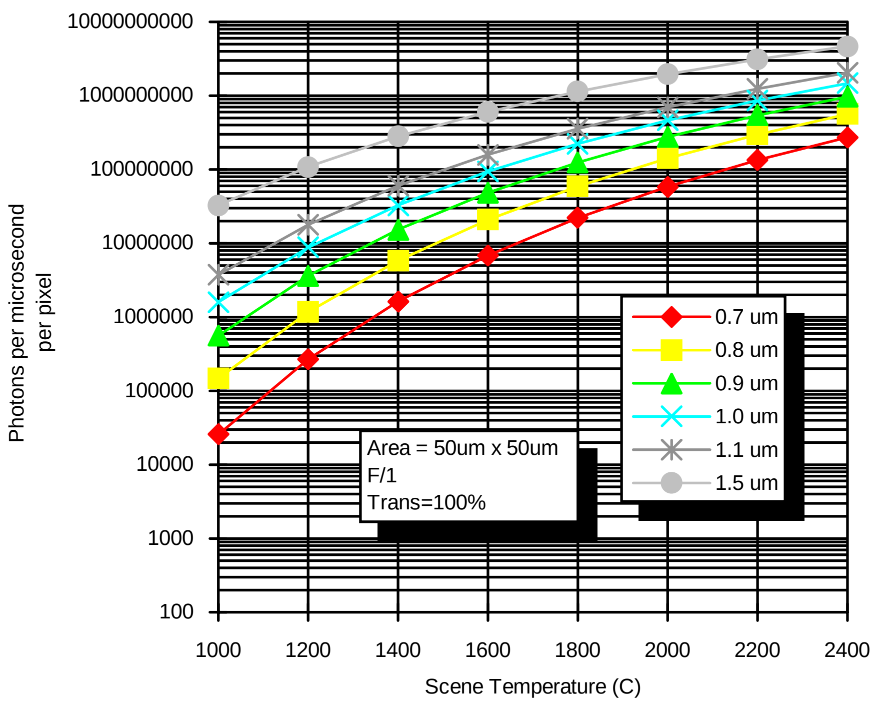

Fig. 4. Photon signal as a function of scene temperature for various cutoff wavelengths.

From this curve, one can see that at the lowest material temperatures (1000^{o}C), the number of usable photons incident on a 50 micron pixel in a microsecond in silicon is 5x10^{6}, and for GaAs it is approximately an order of magnitude less, or 5x10^{5}.

In this imaging scenario, it is also important to calculate the scene contrast, since temperature variations across the material may be of considerable interest. This quantity is effectively:

$$\text{contrast} \equiv \frac{1}{\Phi}\frac{\partial \Phi}{\partial T} \quad (\text{in degrees}^{-1}) \qquad \text{Eq. 4.}$$

This is plotted in the figure below, as measured in percent change per degree C, as a function of scene temperature for various cutoff wavelengths.

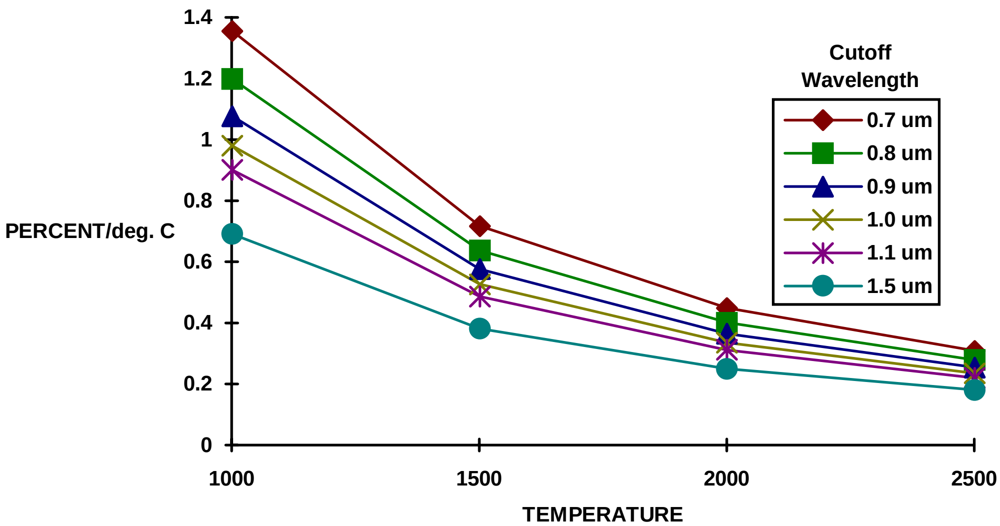

Fig. 5. Scene contrast as a function of scene temperature, for various cutoff wavelengths.

The plot shows that as temperature is increased, the contrast (as defined above) decreases and that as the cutoff wavelength is extended, the contrast also decreases. In general, the contrast is of the order of 0.5% per ^{o}C. For composite materials, the contrast may be dominated by variations in the emissivity across the surface of the material, rather than temperature.

Detector quantum efficiency, η, is a measure of the ratio of photons-in to electrons-out. Quantum efficiency for many detector materials is typically of the order of 40% and is function of wavelength. Here, it is defined to include reflection losses. In addition, in a given pixel, the active area of the detector may be less than the area of the pixel in order to accommodate readout circuitry. The ratio of active area to total pixel area is the detector fill-factor, $f_{f.}$ Fill-factors range from nearly 100% for scientific CCDs to 20% for interline transfer CCDs for television applications.

The total number of carriers, N, generated by the detector depends upon the integration time, Δt, fill-factor and quantum efficiency, according to:

$$N = \Delta t \, f_f \, \eta \, \Phi \qquad \text{Eq. 5.}$$

To calculate the number of carriers collected by the photodetector, we choose an emissivity value of 0.1, assuming that most liquids are fairly reflective and hence have low emissivity. We use Δt of one microsecond for the one megaframe per second requirement, a camera f-number of 1.4, a fill-factor of 0.4 assuming a 50 micron pixel pitch, a detector quantum efficiency of 40% to include reflective losses. (Once the photons are in the material, the internal quantum efficiency can be much higher). The photon flux is that calculated above. Finally, GaAs, InGaAs and silicon are the only materials considered seriously for the imaging system. The carriers collected per frame is presented below.

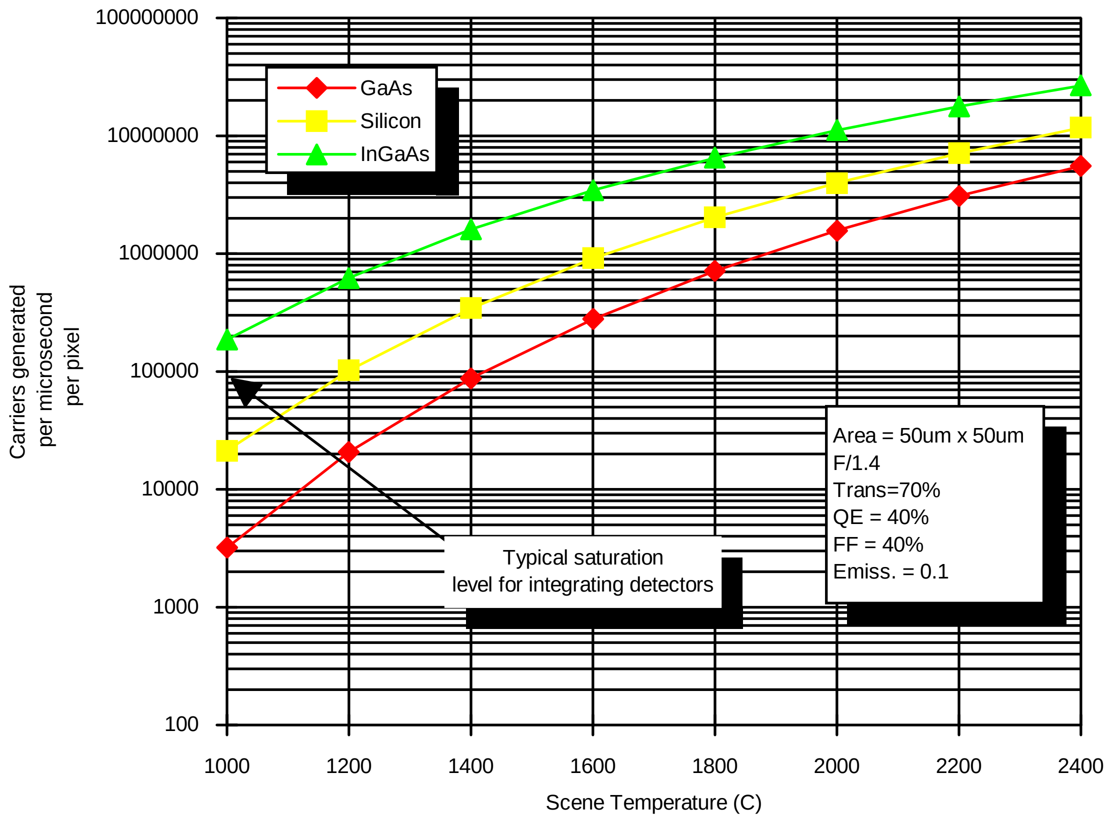

Fig. 6. Output detector signal for GaAs, silicon, and InGaAs detector arrays.

It is observed that silicon has an approximately seven-fold advantage over GaAs at the lowest scene temperature, but the advantage diminishes to a two-fold advantage at 2400^{o}C as the material's emission peak shifts to lower wavelengths. A similar advantage of InGaAs over silicon is observed. It is also observed that coverage of the full scene temperature range without additional exposure control (i.e. aperture closure) requires a dynamic range of at least 1000, and preservation of scene contrast implies an additional factor of 100 or more. It is judged that this is too severe of a requirement for megaframe rate imaging since the A/D converter would also require the same dynamic range. Since aperture control is not difficult, especially in a manned environment, it is presumed.

Clearly, in the case of 1,000 frames per second imaging, one merely multiplies the above scale by 1,000.

STATE-OF-THE-ART DETECTOR ARRAYS

Detectors in GaAs, silicon, and InGaAs are addressed. The major differences in the materials are (1) photonic absorption, (2) technological maturity, and (3) intrinsic speed. The absorption coefficients (α) of various materials is shown below in fig. 7. Flux penetration falls off exponentially according to:

$$\Phi(x) = \Phi e^{-\alpha x} \qquad \text{Eq. 6.}$$

The absorption of photons is given by the derivative of the flux penetration and each absorbed photon yields a carrier to be detected. The generation rate of these carriers in an active thickness d is given by:

$$G_\lambda = -\int_0^d \frac{\partial \Phi}{\partial x} dx = \Phi(1 - e^{-\alpha_\lambda d}) \qquad \text{Eq. 7.}$$

A practical limit to d is between one and ten microns. Thus, to have at least 10% of the photons absorbed in the 10 micron thick layer requires a value of α greater than 100. For a 1 micron thick layer, the required value of α is 1000.

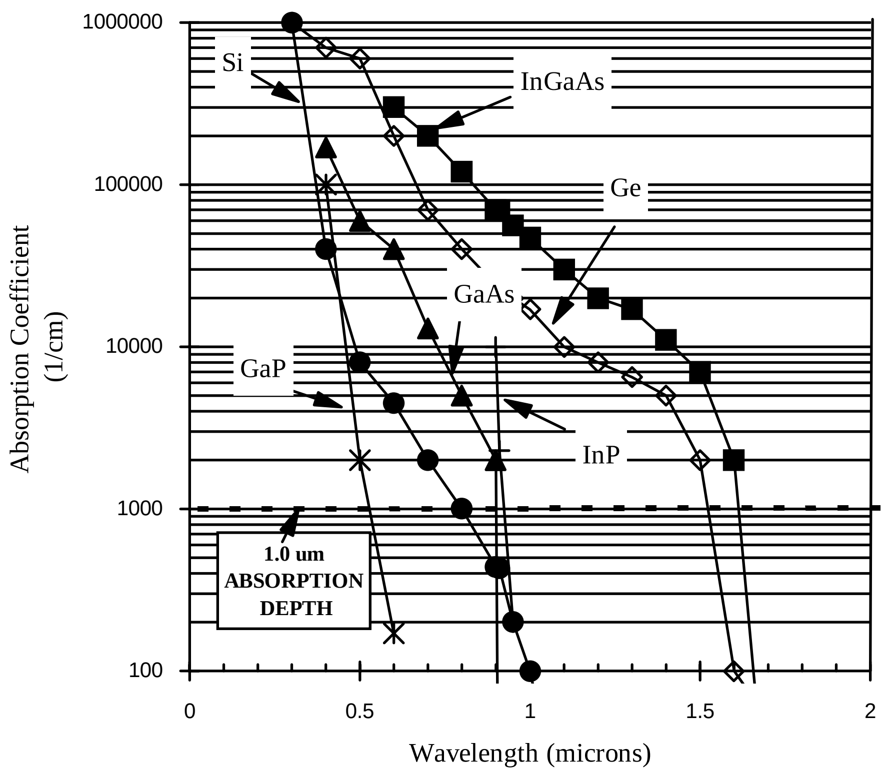

Fig. 7. Absorption coefficients of various detector materials.

As can be seen in fig. 6., silicon's absorption coefficient drops relatively slowly compared to GaAs and InGaAs. Thus, while it may have a wavelength cutoff value of 1.1 microns, *in a practical detector, the cutoff response of silicon will be limited to approximately the same value as GaAs.*

Silicon

Silicon charge-coupled devices (CCDs) are presently ubiquitously employed in imaging systems. They are a well-developed technology for video imaging (television broadcasting, home camcorders, surveillance, etc.) and are used by JPL in scientific imaging systems aboard spacecraft. Table 2 compares some characteristics of commercially available sensors.

Table 2. Comparison of CCD sensors.

"Typical"	Television CCD	Scientific CCD	HDTV CCD	High-Speed CCD imager
Format	512x512	1024x1024	1920x1250	128x128
Frame Rate	30 f/s	0.02 f/s	30 f/s	2,000 f/s
Data Rate	8 Mp/s	50 kp/s	72 Mp/s	32 Mp/s
Parallelism	1	1	2	16
Shift Rate	8 MHz	0.05 MHz	36 MHz	2 MHz
Readout Noise	20 e rms	3-5 e rms	20 e rms	30 e rms
Fill-Factor	30%	90%	40%	70%

CCDs operate by shifting charge through the semiconductor, and their performance is limited by the fidelity of the transfer process. The fidelity (a.k.a. charge transfer efficiency or CTE) degrades as the transfer rate is increased and the image tends to smear out as the signal from one pixel mixes with adjacent pixels. Noise is primarily added by the output amplifier, and the noise has a minimum value near the frequency used by the JPL CCDs; hence their slow readout rate. In the case of high speed imaging where more than one amplifier may be operating in parallel to increase effective readout rate, cross-talk between adjacent amplifiers can become a significant source of signal deterioration. This is especially true in silicon which does not have an insulating substrate.

Presently available devices do not meet the requirements for either the 1024x1024 kiloframe imaging rate, or the 128x128 megaframe rate imaging rate.

The slow diffusion of carriers generated deeply in silicon is a problem for high speed imaging since the resultant image lag would be highly disruptive. A filter to cutoff longer wavelength photons will be necessary, yielding a spectral response range similar to that of GaAs.

Infrared silicon CCDs have been formed using platinum silicide detectors on the surface. These devices are typically responsive in the 3-5 micron range with quantum efficiency of approximately 1%. The two problems with this technology for the MCPF application are that the CCDs are as slow as the CCDs described above, and the platinum silicide detectors require cooling to approximately 80K.

GaAs

Gallium arsenide (GaAs) has been used primarily for high speed circuits since GaAs is a higher speed material than silicon. This intrinsic speed advantage is important in the application considered here. GaAs also, by virtue of its greater bandgap, has lower dark current than silicon. For such high-speed imaging considered here, this would only be an advantage if higher-than-room-temperature operation was an issue. (To have the image sensor staring at a hot body for long periods of time may require focal-plane cooling). In general, GaAs is a less mature technology as evidenced by the scale of integration in silicon circuits compared to GaAs. GaAs CCDs have been fabricated and clocked at rates in excess of 1 GHz - at least an order of magnitude faster than silicon and sufficient for the applications considered here. The largest fast CCDs built in GaAs have been approximately 64x1 pixels. Varian has built some 32x32 slow AlGaAs CCDs. It is unlikely that a 1024x1024 CCD array could be effectively built in GaAs in the near term, but a 128x128 array or is certainly feasible. Other imaging architectures such as the APS may be able to be built in larger sizes, perhaps as large as 512x512.

InGaAs

Indium gallium arsenide (InGaAs) is a major material for the optoelectronics business (e.g. fiber optics) because its cutoff wavelength corresponds well to the wavelengths that propagate well in optical fibers. InGaAs is also a high-speed material, and is somewhat faster than GaAs. The major disadvantage to InGaAs is that its smaller bandgap makes it have higher dark current than either silicon or GaAs. At high frame rates this is less of an issue, provided modest thermo-electric cooling can be provided to the focal-plane (at a cost of several watts). The first InGaAs CCDs have just been reported in the literature, so that CCD technology is very immature and not expected to be ready in time for this project. Other imaging architectures besides CCDs such as the APS can be envisioned, though InGaAs circuitry, as a technology, is less mature than GaAs and more difficult to realize.

Table 3. Summary of Different Materials Prospects

	Silicon	**GaAs**	**InGaAs**
Effective λ Cutoff	0.9 um	0.9 um	1.6 um
Bandgap	1.12 eV	1.4 eV	0.76 eV
Electron Sat. Velocity	100,000 m/s	200,000 m/s	280,000 m/s
Imager Maturity	High	Low	Low
Potential for Scenario 1	Good	Medium	Medium
Potential for Scenario 2	Poor	Good	Good

IMPLEMENTATION CONCEPTS

There are two aspects to the implementation of a high speed imaging system for the MCPF. First, as has been extensively discussed already, is the choice of focal-plane technology. A second, equally important and difficult consideration is the camera system design that includes drive electronics, signal chain electronics such as preamplifiers, amplifiers and analog-to-digital converters, and data storage. The camera system will be generating data at the rate of 1 billion pixels per second, albeit for a short interval.

Focal-Plane Technology Using CCD Arrays

In scenario 1, a 1024x1024 imager is desired, operating at 1000 frames per second. Silicon CCDs operate fairly comfortably at data rates up to 10-20 MHz, and HDTV sensors have been operated at rates up to 30 MHz per channel. Consider a reflective pyramid used (as in WF/PC) to divide the field of view into four (4) 512x512 regions, so that each region has its own image sensor. If each 512x512 image sensor is readout in 4-quadrant mode (256x256), then the data rate from each quadrant is $256 \times 256 \times 10^3$, or 65.5 MHz. Using dual channel devices, it conceivable to reach this data rate using silicon CCD technology operating at 33 MHz. The total number of parallel outputs would be 32 to achieve the total data rate of 1 GHz. This is a brute-force approach to utilize silicon CCDs.

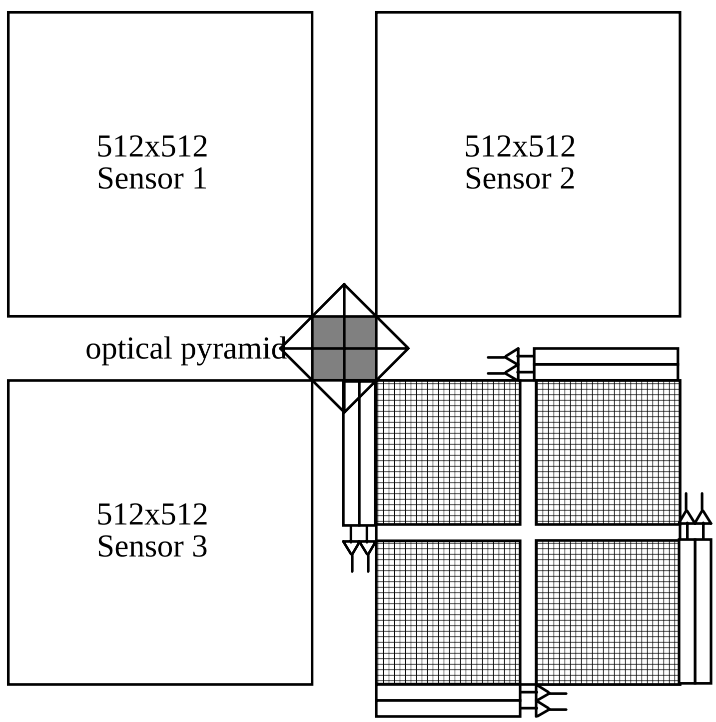

Fig. 8. Achieving 32 parallel outputs in a 1024x1024 sensor. Only one of four 512x512 sensors is expanded to show four-quadrant, two-channel readout.

Since silicon CCDs are limited to approximately 30 MHz in imagers, there is no alternative to achieving 1 GHz data rates other than applying 30-fold parallelism in the readout.

In the case of scenario 2, one can similarly apply parallelism. For a 64x64 sensor operating at 1 megaframe per second, 128-fold parallelism is required. Thus, one could devise an architecture in which the sensor is divided into two halves of 64x32 each, and then each 32-pixel long segment would have its own readout. This is illustrated below:

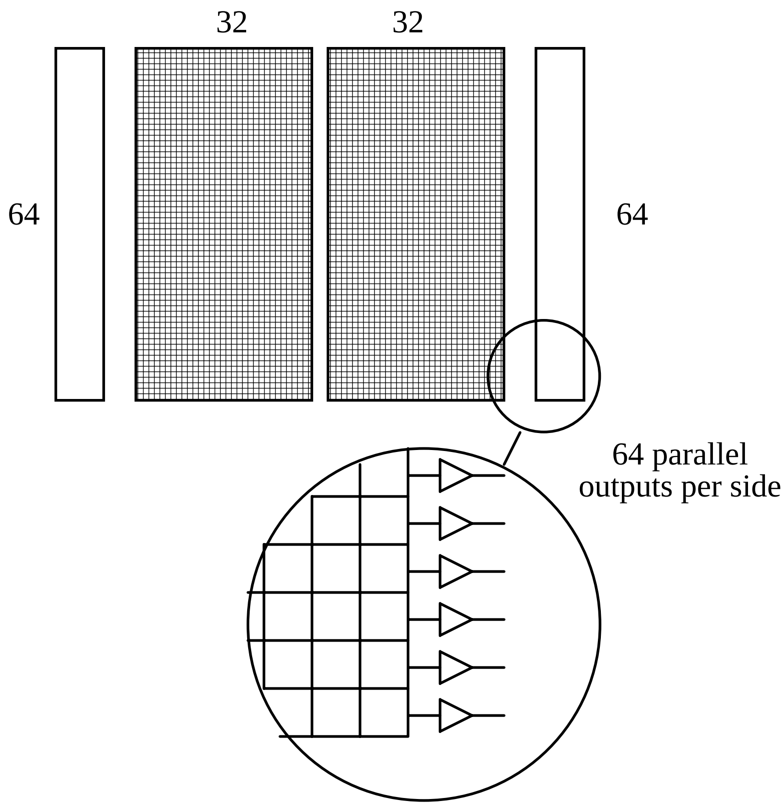

Fig. 9. Massively parallel (x128) output image sensor for 1 Mf/s imaging.

There would be many concerns with such a sensor architecture. Channel crosstalk would likely be a "show-stopper", especially since each channel is to be 32 MHz.

It should also be noted that in order to achieve 32 MHz operation, small pixel sizes would be required, e.g. of the order of 10 microns x 10 microns. The analysis for the signal level assumed a pixel 25 times larger, so the signal level should be decreased by approximately a factor of 25, putting the successful imaging of 1000^{o}C scenes in jeopardy.

A small GaAs CCD array (64x64) with a similar architecture should also be considered. Since GaAs CCDs have achieved speeds as high as 1 GHz, the limitation in the system is the A/D converter in the signal chain. The degree of parallelism required is determined by the maximum A/D conversion rate, and is likely to be of the order of 64. Since the GaAs electron mobility is so much higher than that of silicon, larger pixel sizes (50 micron pitch) can be considered. The semi-insulating substrate typical of GaAs technology should eliminate channel crosstalk problems.

Focal-Plane Technology Using APS Arrays

A new type of sensor concept is presently being proposed for study by NASA and SDIO. This type of sensor is called the Active Pixel Sensor (APS), and is characterized by having one or more transistors within the unit cell. Unlike a CCD, there is no shifting of signal charge required to readout the image. Thus, the upper limitation on pixel size becomes less important, though pixels smaller than 25 microns x 25 microns require new device concepts such as the charge-modulated device transistor. The speed of APS arrays implemented in silicon are not expected to operate much faster than the fast silicon CCDs, though the comparative performance will likely be higher for APS.

Implementation of the active pixel sensor is much more readily achievable in GaAs and InGaAs compared to CCDs, and the speed of an APS array in GaAs or InGaAs could be quite high - making achievement of the very high speed imaging scenario (2) plausible. An example of an array architecture implemented in GaAs or InGaAs APS technology is shown below:

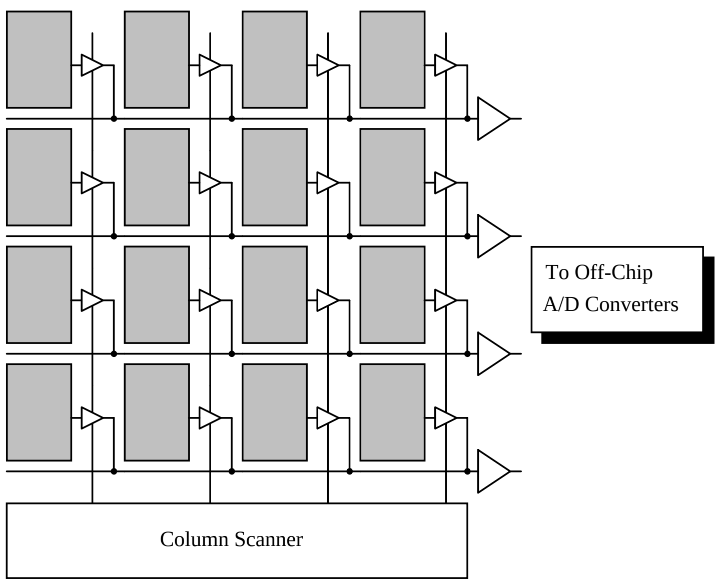

Fig. 10. Active pixel sensor (APS) architecture for very high speed imaging.

Each pixel contains a photodetector and selectable preamplifier. The preamplifier drives the row line which is terminated by a second amplifier. The second amplifier drives the signal off-chip to an A/D converter. In the figure each row has its own amplifier, and columns of amplifiers are selected by a column scanner circuit. For a 64x64 imager operating at 1 megaframe/sec, the 64-fold parallelism of readout yields an output data rate per row of 64 MHz, easily achievable in GaAs or InGaAs. Since these devices are typically fabricated on semi-insulating substrates, cross-talk is expected to be considerably reduced compared to silicon. While the APS technology requires as many amplifiers as pixels, it should be noted that only one column of amplifiers is selected at any one time, keeping power dissipation on chip at a minimum. The fill-factor for the APS arrays is estimated to be 40%-50%. Also, the column scanner circuitry need not be integrated on chip.

Camera System

The camera system includes optics, filters, cooler, drive electronics, signal chain electronics, A/D converters, and digital storage. The two scenarios generate vast volumes of data in the blink of an eye - either 4 Mbytes in 1 msec or 100 Mbytes in 100 msec. A generic block diagram is shown below:

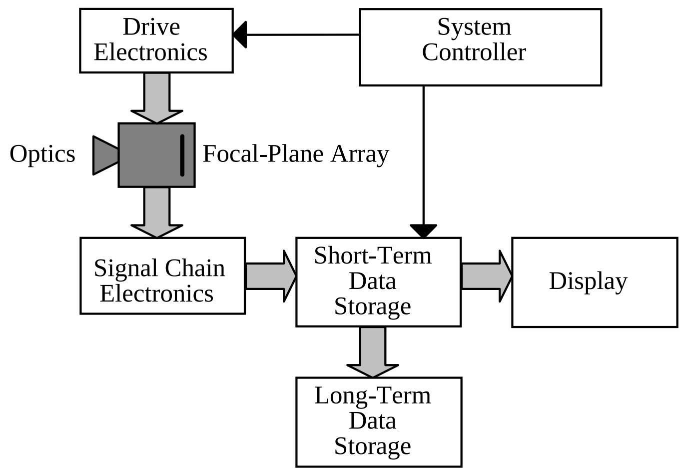

Fig. 11. Block diagram of a high speed imaging camera system

The major concerns for the camera system are in the signal chain electronics - primarily the A/D converters, and in the data storage system. It is likely that the parallelism inherent in the focal-plane architecture will need to be extended to the signal chain electronics (e.g. 64 independent A/D converter signal chains) as well as to the data storage architecture. This way, the 64 MHz per channel data rate of the very high speed system is achievable throughout the system. While complex and high speed, the camera system (aside from the focal-plane array) is not considered to be a show-stopper.

CONCLUSIONS

The major challenge in realizing the Microgravity Containerless Processing Facility high speed imaging system is in the focal-plane technology. A different technology is indicated for each scenario.

The imaging problem was analyzed and it was found that while the photonic signal from the hot material will peak in the SWIR, the visible part of the spectrum is sufficient for imaging. Thus, the leading candidate detector materials in view of the large array sizes required are silicon, gallium arsenide (GaAs), and indium gallium arsenide (InGaAs).

In the first scenario of high resolution imaging at 1,000 frames per second, a silicon focal-plane array is indicated due to the relative immaturity of other materials systems vis-a-vis the manufacturability of large arrays. Reducing the format requirement to 512x512 can significantly simplify the optical design, given the readout rate restrictions (~33 MHz) on CCDs since these rates are not anticipated to be improved in the near future, and result in a four-fold reduction in signal chain electronics. The use of GaAs for a 512x512 APS array is also conceivable, with a reasonable development effort.

In the second scenario of very high speed imaging at 1,000,000 frames per second, a GaAs or InGaAs active pixel sensor (APS) array is indicated. This focal-plane would also require development since such an APS array has not yet been demonstrated. InGaAs has better imaging properties, but a less mature circuit technology. A GaAs APS array could be potentially manufactured in a commercial foundry reducing development time and risk. The present study indicates that the imaging properties of a GaAs array would be sufficient for the application.

Table 4. Recommendations for Focal-Plane Technology Development

	Scenario 1 High Resolution	**Scenario 2 Very High Speed**
Near Term Implementation (<5 years)	Not easily possible, Can use smaller CCD array.	Not easily possible, Could have an A/D for each detector
5 year Implementation	Develop HDTV-derivative silicon CCD technology, split image into 4 CCDs.	Develop GaAs APS technology. Perhaps InGaAs for better QE.
Long Term Implementation (>5 years)	Develop GaAs APS technology for large array sizes.	Develop InGaAs APS technology.