Million Frame Per Second CCD Camera with 16 Frames of Storage

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Keywords: High speed camera, High speed CCD, On chip storage

1.0 Abstract

Ultrafast imaging is an important need for the development, control, and evaluation of modern air-deliverable weapons systems. Recent advances in optical imaging such as speckle Interferometry can potentially improve DoD capability to deliver munitions and armaments to targets at long ranges, and under adverse seeing conditions. Ultrafast imaging is also required for flow field optical image analysis for hypersonic propulsion systems. Silicon Mountain Design (SMD) has built such an imager so that high quality images can be obtained for relatively low cost. The SMD-64K1M camera is capable of imaging 1,000,000 frames per second using a 256 x 256 array with the ability to store 16 frames with true 12 bits of dynamic range. This camera allows researchers to capture multiple high speed events using solid state technology housed in a 53 cubic inch package. A brief technical overview of the imager and results are presented in this paper.

2.0 Camera Description

Figure 1. SMD 64K1M Million Frame per Second Camera.

The SMD-64K1M, so named by virtue of 64k pixels operating at 1 million frames per second, uses a proprietary CCD architecture allowing up to 16 frames to be stored on the CCD, which can be read out at a later time. The camera is housed in an enclosure measuring 4 inches on each side, to which a C mount lens can be attached.

This camera was developed on a SBIR Phase I effort from the U. S. Air Force Wright Labs. As a result of the short development time and technical achievement for this camera, Silicon Mountain

Design won the SBIR technology of the year award [1] in 1996. In comparison to other high speed cameras, the small, lightweight aspect of the camera and relative low cost provides users with a new tool to image at high speeds and receive immediate results without having to wait for film to be developed.

2.1 Disadvantages of High Speed Film Cameras

Film based cameras, such as rotating mirror framing cameras and the like, have been used for over 50 years to acquire high speed imagery. However, they possess several disadvantages. First, since the shuttering is performed by some means of mechanical rotation, the mirror or prism must be spun up to the operational rotation before the sequences can be acquired. Furthermore, during a portion of the rotation, there is often an angular segment where there is no film. Thus, the event must be triggered by a synchronization signal from the camera, when the camera can take data, rather than the camera being triggered by the event, which is more preferable.

Film cameras are also quite large and require special lenses to operate at the high F/#s (i.e. F/200) necessary for aperture shuttered framing cameras. For very high framing rates, helium is required to rotate the shuttering mechanism. As a result, framing cameras are not very portable and usually remain in a static location near the test facility. A further disadvantage of film based cameras is the fact that there is a directive within the U.S. Dept. of Defense to eliminate the use of film for their testing programs due to the hazardous materials involved in the use and processing of film.

High speed film cameras use film, which obviously requires processing. At the High Explosive Research and Development (HERD) facility at Eglin AFB, it can take up to a week for the film to be processed and another week for digitizing the film images to a computer compatible format. Thus, the experimenter often has two weeks to wait and find out if some parameter needs to be changed in the experiment. This is contrasted with the ability of a solid state based camera to provide immediate feedback to the experimenter. During our tests at Eglin in May 1997, experimenters had immediate feedback, for the first time, of high speed imagery which allowed them to make some changes to the experimental setup. This not only helps the researcher to get his data quicker, but allows him the ability to perform multiple experiments during his scheduled time at the test facility. With film based cameras, since he has to wait a week or so, he may not have access to the test facility until some later time. During our tests in May 1997, our experiment turn around time was limited only by the necessary safety stand-down time (1 hr) and the experimental setup (20 min).

This camera was developed for the U.S. Air Force under a contract to provide an imager capable of recording ultra-high speed events. As part of the Air Force's task to maintain the national security, it is necessary to develop advanced weapons and munition systems, most of which involve explosives. High speed cameras are needed as diagnostic tools to measure several parameters of explosives including the speed of the explosion wavefront as it propagates through the material. The shock wave associated with explosives moves rapidly at speeds between 5 to 10 mm/μsec. One common test to measure the detonation speed of an explosive material is to perform a "rate stick test". This test involves forming a cylindrical prism of the test explosive material and initiating detonation at one end of the stick. Then, using various high speed diagnostics, the detonation rate can be measured by observing the propagation of the shock wave down the length of the stick.

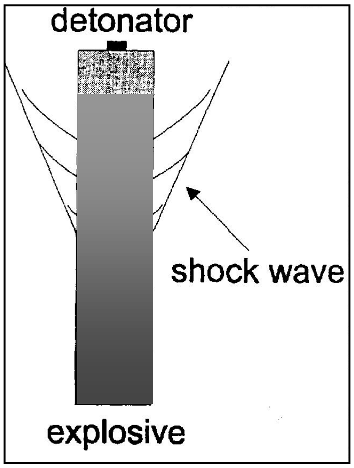

Figure 2. Rate Stick Test

Weapons development is not the only use of explosives research, and today one of the active areas involves the safety of the munition stockpiles. Understanding the dynamics involved in how munitions explode, and the necessary conditions for detonation, enables those responsible for storing large quantities of munitions to store them in a configuration where an accidental explosion of one bomb does not create a chain reaction destroying the entire storage depot.

2.2 CCD Design

The custom designed CCD has been designed to allow fast charge transfers to the memory sites, on the order of 100 ns[2], however, other restrictions currently place a limit at 1 μs for a complete transfer to memory. This initial device has been improved on and the next generation imager will allow transfers in 100 ns. Once the memory is filled, the image sequence is read out of 4 on chip amplifiers t 20 Mpixels/sec. In this way, the 64K1M can be readout in 16 ms, or at 60 sequences per second. Thus, after acquiring 16 frames at 1 million frames per second, the camera can be ready to acquire another 16 frames in 16 ms.

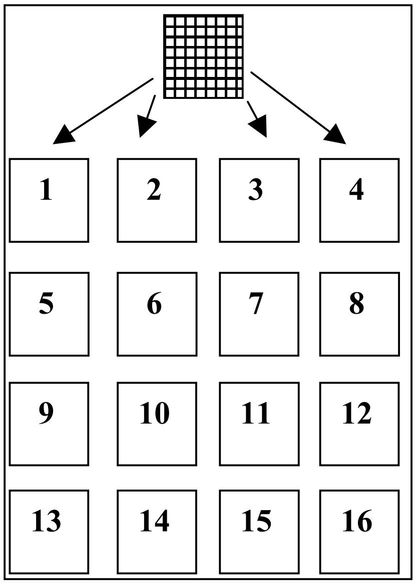

Figure 3. Pixel Logical Arrangement

The CCD is fabricated on a relatively low resistance p substrate to permit fast transfers to the memory segments surrounding each pixel. The transfer gates are basically MOSFET type structures so that a positive pulse applied to the transfer gate causes a depletion region directly underneath the gate, allowing charge to flow from the "active area" of the pixel into the memory section. Each memory site has its own transfer gate and accurate timing must be employed so that two transfer gates are not turned on at the same time, which would cause the signal charge to be split into two different memory sites. When the image sequence has been acquired, each memory site is transferred to the output amplifier and read out. Thus, the image sequence is transferred in order of acquisition to the frame grabber.

The CCD also employs a lateral anti-blooming structure to protect against over-saturation of a pixel. The anti-bloom gate can also be used to provide a method of arming the camera to begin taking data without being influenced by dark current. This is done by holding the anti-bloom gate low while the camera is armed, but not triggered, causing any generated electron to flow into the anti-bloom channels next to the pixel (see Fig 4). Then, when the camera is triggered, the anti-bloom gate is raised forming a barrier to lateral diffusion causing the generated electrons to collect in the potential well.

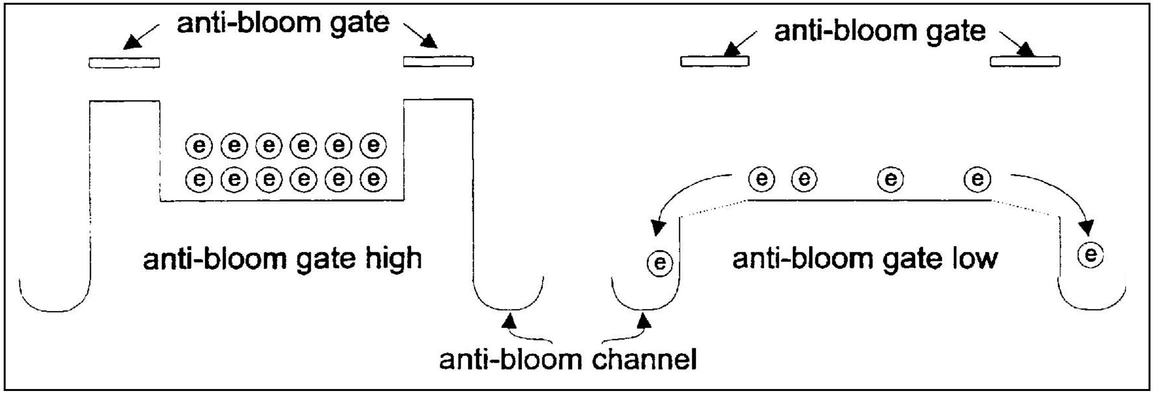

Figure 4. Anti-bloom gate shuttering

2.3 Modes of operation

All modes of operation are controlled by the host PC which is linked to the 64K1M camera via a RS-232 link. The user is provided with several dialog boxes to change the integration time, frame rate, anti-bloom exposure control, and CDS gain. After an image sequence has been taken, the software displays the image sequence on the computer monitor and allows the user to perform several image processing routines before saving the image to disk.

3.0 Camera Specifics

3.1 Camera Specifications

• Imager format	256 x 256 x 16 monochrome
• Dynamic range	12 bits
• Pixel cell size	56µm x 56 µm
• Sensitivity	8 µV/e
• Size	3.9” L x 3.7” W x 3.7” H
• Operating temperature	0 – 45 deg. C
• Weight	30 oz (850 g)
• S/N ratio	70 dB
• Power consumption	10 Watts
• Dark current	approx. 8 nA/cm^2
• Lens mount	C mount
• Frame rates	60, 100, 200, 500, 2000, 10 kfps, 200 kfps, 1 Mfps
• Readout rate	60 image sequences per second

3.2 Hardware Interface

The interface to the camera is composed of a RS-232 link between the camera and computer for camera control, a parallel RS-422 interface for transmitting pixel data, and power is supplied for the GND, 5V, +15V, -15V needed to drive the camera.

The camera can be placed in an "armed" mode, as explained earlier, waiting for a rising edge TTL signal on the TRIG input SMB connector on the back of the camera. When the rising edge is detected, the camera takes 16 frames worth of data at the specified frame rate, and immediately sends the data to the computer. On board A/D converters digitize the video signal to true 12 bits, which are then sent via a parallel RS-422 interface to a digital frame grabber within the computer.

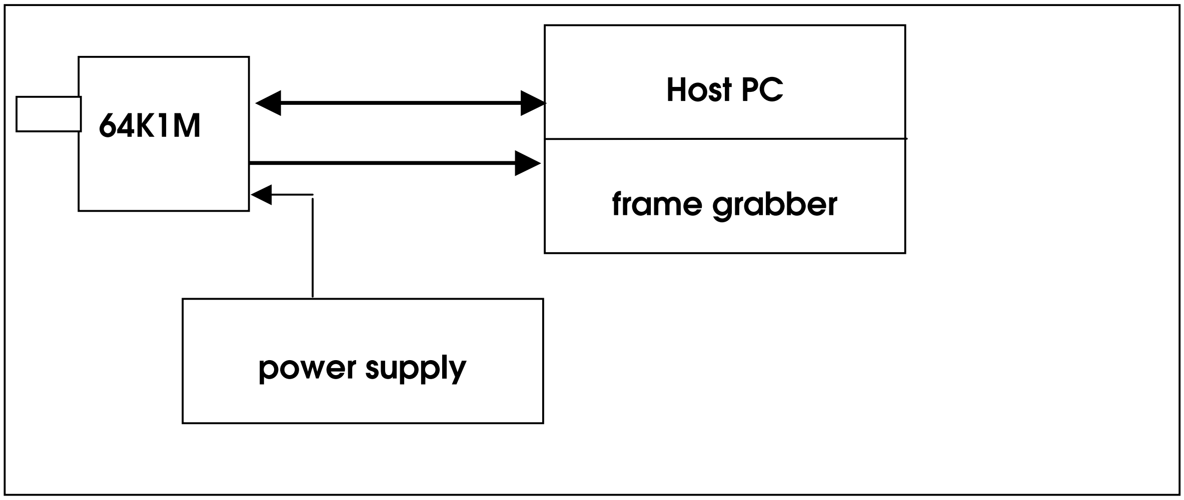

Figure 5. Block Diagram of 64K1M

3.2 How Tested

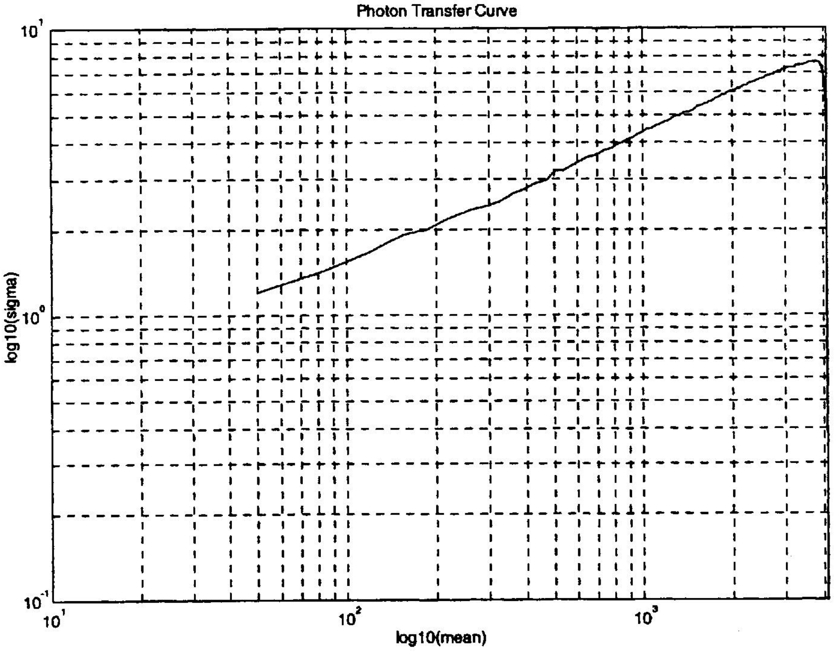

Figure 6. Photon Transfer for 64K1M cameras

Each of our cameras are tested to insure proper operation and conformance to specification. The photon transfer technique[3] has proved invaluable for measuring the linearity, read noise, full well capacity, radiometric calibration, and dynamic range of the CCD.

Figure 6 shows a typical photon transfer curve for the 64K1M series cameras. The read noise is calculated to be 1.09 ADU (A/D counts). The full well capacity of the imager is measured to be 213,000 electrons. Differential non-linearity is measured to be at most .5%. The camera system gain is 52 electrons per ADU. Thus, the dynamic range is 71 dB (11.8 bits)

4.0 Pictures / Results

4.1 Hopkinson Bar test

The Hopkinson Bar test is diagnostic tool allowing researchers to generate planar shock waves within a solid metal cylinder which is in contact with the device under test. At the Graduate Engineering Research Center at Eglin AFB, the Hopkinson Bar test was used to measure the strength of concrete and how cracks propagate. In this case, the metal cylinder is in contact with a piece of concrete that has a slit cut in it. The concrete is hit with the shock wave from the left side and cracks can be seen to propagate through the image sequence.

Using these images, researchers and engineers can study crack formation in concrete to understand how to build concrete structures that can survive earthquakes, or to develop weapon systems that can penetrate hardened bunkers. The vertical smear present is due to a long duration flash which caused corruption of the memory transfers. In normal operation, a shorter Xenon flash strobe duration is used.

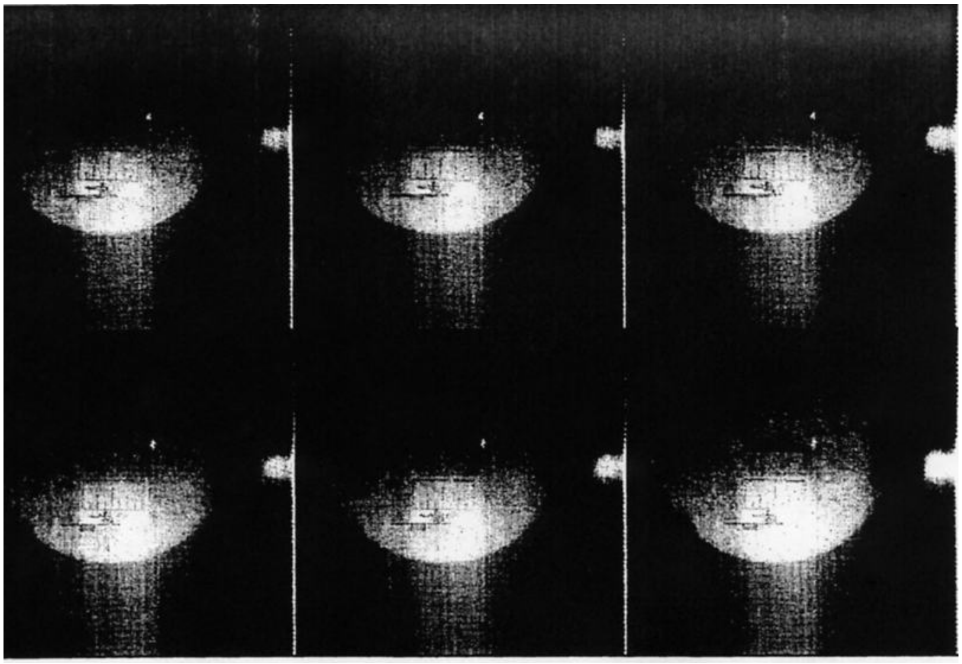

Figure 7. Six pictures showing images of Hopkinson Bar Test (6 out of 16)

4.2 HERD

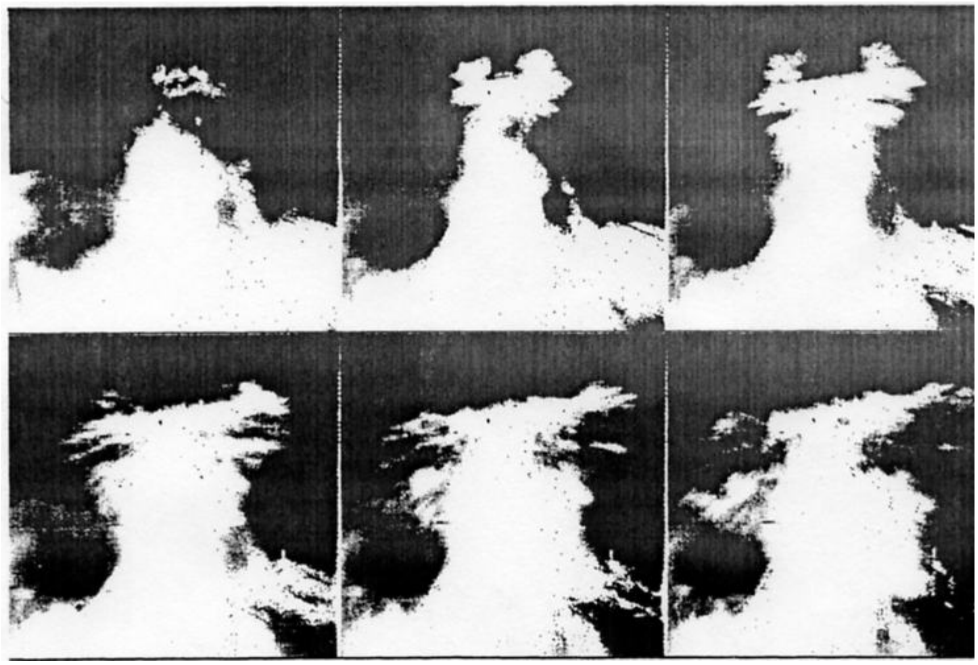

Figure 8. Six pictures showing exploding rate stick at HR facility (6 of 16)

The above picture was taken at the High Explosive Research and Development facility at Eglin AFB. The cylinder object extending vertically in the frame is the rate stick and it is ignited from the top using a bridge wire activated booster. The scene was also illuminated with an argon candle placed about 1 meter from the scene. Time and budgetary constraints allowed only one rate stick test, and no one knew how much light the rate stick would emit during detonation. Since the technicians and researchers had only used film based cameras, we had to make back of the envelope calculations to set the exposure (integration) time. As you can see from the pictures, the camera was more sensitive than we had calculated, but since the camera has 12 bits (4096 levels) of dynamic range, we were able to acquire a usable image sequence.

5.0 Future Developments

Silicon Mountain Design is now in the process of improving the capabilities of this camera to image at speeds of 10 million frames per second, and another development effort will increase both spatial resolution and number of images stored. The 256K1M high resolution camera will provide users with 512 x 512 resolution images with the ability to store 64 frames at 1 million frames per second. The imager is also being designed to be capable of color imaging. The dynamic range will still be 12 bits, and the readout will be at 20 MHz corresponding to 5 sequences per second.

6.0 Summary

Silicon Mountain Design's 64K1M camera provides users with the ability to record 16 images at various frame rates up to 1 million frames per second with 12 bits of dynamic range. The relative low cost enables researchers with a tool to study ultra-fast phenomena that previously was cost prohibitive.

7.0 Acknowledgements

This work was supported by the U. S. Air Force under contract #F08630-96-C-0066. We wish to thank Don Snyder, Bob Webb, and the Wright Laboratory Instrumentation Branch MNSA for their support and encouragement during this development effort.

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[1] 1996 SBIR Technology of the Year Award Grand Winner. Presented at Anaheim, CA, Oct. 30, 1996.

[2] Carnes, Kosonocky, and Ramberg, “Free Charge Transfer in Charge-Coupled Devices”, IEEE Transactions on Electron Devices. Vol. ED-19, no. 6, June 1972.

[3] Janesick, Klaasen, Elliott. “Charge-coupled device charge collection efficiency and the photon transfer technique.” Optical Engineering Vol 26. No. 10. Oct. 1987.