

**Failure Analysis, Fault Determination and Isolation  
of Laser-Damaged Interline Transfer CCDs**

**Submitted by  
6052 Failure and Materials Analysis Lab  
NSWC Crane  
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# Introduction

Recently, NSWCrane was approached to help perform failure analysis, fault determination and isolation on laser damaged interline transfer Charge Coupled Devices (CCDs). The initial task objective was to understand device construction/operation and determine which laser-induced defects generate various failure modes viewed on the video output of the CCD. Better understanding of CCD chip structure and operation, as well as its failure modes, should facilitate better laser hardening techniques.

After considerable effort was spent acquiring data and information on device structure and operation, fault sites that caused various failure modes on the CCD output were analyzed. The failure modes included, but were not limited to the following:

- Black Spots
- White Spots
- Colored spots
- Horizontal Black Lines
- Vertical White Lines
- Blooming Cross-Like White Spot
- Waterfall Effect
- Half Blank Screen
- Blank Screen

Upon completion of both construction and fault site analysis on numerous CCDs, theories were developed for various chip behaviors observed after damage by a laser beam. Simulations were then developed and tested to verify findings.

The intent of this document is to provide the reader with an understanding of the work accomplished in support of this effort and provide the insight necessary to introduce new and better laser hardening techniques.

# **Chip-level Basics of Failure Analysis**

This section will discuss the process steps and techniques that are utilized while performing failure analysis on Charge Coupled Devices (CCDs). The processes and techniques are discussed below in typical order that they are undertaken during failure analysis. The intent of this section is to provide information to the reader that will allow a better understanding of the problem solving process.

## **Review of Background Data Associated with Anomalous CCDs**

The history and data of what has been done to a given CCD is thoroughly reviewed and addressed. This includes the number and location of laser shots, energy and frequency range, video image output of the device after each shot, as well as other conditions related to the shots or response of the component. All related data, whether jpgs, gifs, Excel files, observations, etc, are reviewed together with the electrical specifications related to a given CCD, so that the exact state and behavior of the device is known and can be confirmed before failure analysis begins. If the unit were fully functional, then a review of the specifications would usually be adequate before proceeding with construction analysis, simulation of failures and deprocessing.

## **Capture Video Output of Operating CCD**

During this step of the failure analysis process, the unit is connected to power and its output is monitored via a video recorder in order to observe the unit's response to given laser damage. When possible, this is done with the lens in place, to help orient the video of the damaged area to the physical location of the damage on the die surface. Light intensity is varied from zero light to bright light to record changes in video output at the location of damage. Depending on the output and the behavior of the CCD, the same operation is accomplished with or without the filter, and with the use of fine focused microscope light or low power laser. This has also proved to be beneficial in determining the exact failure modes of the individual laser shots.

## **Package opening**

Generally, the cover glass needs to be removed to complete the die inspection and photo documentation process and also to de-process and identify depth and severity of the laser damaged areas. Removal of the cover glass is accomplished by milling around the attached area of the cover glass until breaching the package cavity. The cover glass is then removed with a small probe or tweezers. The exposed device is cleaned with alcohol, air and ultrasonic if needed. During this process, it is important to avoid disturbing bond wires or permitting glass or package chips to damage the organic covered array area. If removal of the cover glass is for the purpose of filling the cavity with fluid and resealing, milling is continued until residual glass is removed and the attachment area is smooth and level. The package is once again cleaned with alcohol and air. The distance between the sidewalls of the package are measured and a diamond saw is used to cut a new cover glass to replace the removed cover glass. Another opening method that has had marginal success, is to plan sand through the cover glass until it is paper thin, place inverted onto a piece of tape, and remove the unit from tape. The cover glass should

remain on the tape. During this technique, the CCD must be removed from the board prior to sanding to avoid damaging the support components. Debris has been the main problem with all opening techniques attempted to date, with the sanding method being the cleanest, but also, the more tedious and difficult to complete. With relatively small areas of laser damage, it is difficult to differentiate optically, even with the use of a wide variety of lighting methods, between the mechanical damage from debris and laser damage. If possible, the damage sites are best identified and documented prior to removal of the clear protective glass. There are several variables that influence the quality of photomicrographs such as, damage size, focal distance and lighting that can, under certain circumstances, make photo documenting the damage unsuccessful.

### **Optical inspection**

Optical macroscopic inspection is utilized to correlate the laser shot damage to the video image output. For this step, it is important to have as many details about shot locations and energies as possible. Locating and accurately identifying the laser shots will allow for the photomicrographs of laser shots to be correctly identified for comparison of the damage on the die surface to the failure mode of the video output. All laser shots are photographed on a high variable power magnification microscope and overall images of the CCD are photographed using low variable power microscopes. As with the initial video output of the device, various lighting conditions, including bright field, dark field, and polarization, are used to optimize inspection and photographic documentation to maximize the information available from each site.

### **Electrical Measurements**

Volt-ohm meter and curve tracer measurements are made on the pins of the device with and without light. Testing on functional, nonfunctional, and damaged array CCDs has not yielded much useful information. However, on-chip probing of undamaged and damaged circuitry using a curve tracer or volt-ohm meter, especially after laser isolation of portions of the circuitry, is instructive and useful. On chip probing often assists in the understanding of the laser shot damage, whether it be to poly-silicon gates, or more extensive and invasive damage.

### **Probe/Laser Station**

The laser station is utilized to remove the topcoat on the die surface and allow access to the underlying circuitry. Selected elements, metal or poly runs, are then removed from the circuitry with the laser to simulate failure modes and verify by electrical measurements the different hypotheses for what conditions are present to cause the resulting anomalous video outputs. This testing is performed while the device is under power to allow monitoring of the video output during the isolation process.

### **Component Preparation**

Before cross section or angle lapping, the CCD device must be removed from its board. The preferred technique is to use a low temperature hot gas solder process to allow removal of the device being evaluated without damaging surrounding components. There are circumstances that require the device to be reinstalled on the board for further optical and functional testing. This is accomplished with the same hot air flow soldering process

as removal. The isolation or damaging of selected pixels in the array or other chip circuitry to simulate or duplicate the behavior and damage that a CCD had upon receipt for failure analysis, can be completed while the CCD is mounted on the board.

### **Package, Glass, Die, Organic Identification, Removal & De-processing**

Once all of the needed information has been obtained from the CCD assembly and CCD device, the cover glass is removed to allow further analysis by FTIR, SEM-EDS, and Transmittance/Reflectance. Identification of the epoxy that holds the cover glass can be identified by FTIR. Once the CCD chip-die has been removed, the organics over the array can be identified by FTIR. Plasma etching, using O<sub>2</sub>, has been found effective in removing the array's cover coat, microlenses, planarity layer, dyes, and other organics to expose the metallization, polysilicon, and oxides above the silicon. The SEM-EDS can identify the metallization and glasses used on the die. Normal chemical methods can then be used to remove the insulating glass, metal, dielectric insulation, polysilicon, etc, to gain access to the silicon surface.

### **SEM Inspection/Analysis**

The areas identified and photographed during optical inspections are typically submitted for SEM analysis, secondary, or backscatter, electron imaging, Energy Dispersive Spectrometry (EDS), 'point' or area elemental spectra and maps. Depending upon the depth and severity of the damage to the die, the SEM photos give a much better image of the damage versus the optical microphotographs. The SEM imaging, together with optical imaging, can also provide indications as to the depth of the damage, whether surface, subsurface, etc. The use of SEM-EDS permits the identification and elemental mapping of the damage sites, which provides additional information about the cause of failure or anomalous chip behavior. The SEM is also utilized after beginning the cross sectioning. The sample can be periodically viewed and documented during the entire sectioning process with much higher resolutions than available with the optical microscopes, providing higher magnification images, elemental identification and maps of the materials in the areas of interest. The SEM inspections also provide additional information to confirm or refine the theories of what has been damaged and why such damage causes the chip to have the observed anomalous functional behavior.

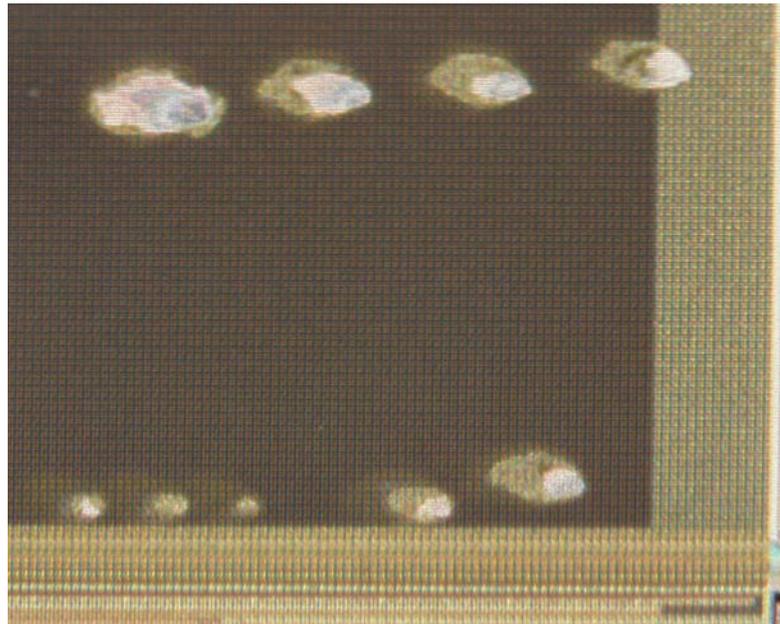
### **Cross Section, Angle Lap/Plan Section/Deprocessing/FIB/and Staining**

Cross sections of various types are very useful in confirming and understanding the CCD circuitry, gate and cell array structure, and composition. On a functional or damaged device, de-processing is accomplished by utilizing a Plasma Etcher to remove the organic cover coat, lenses, planarity and dye layers. Wet chemical processes can then continue the removal of glass, metal, interlayer conductor glass, polysilicon gates, etc. down to the silicon die. Cross sections perpendicular to or at a very slight angle with respect to the side, just off the row and column line of the array will permit visibility of the layers in-situ of the whole cell structure by moving along the section. Staining of the silicon, which etches diffused, implanted, epitaxial and other regions to a different degree, depending on the dopant impurity level, provides visibility into the subsurface silicon structures. Perpendicular cross sections at a 45 degree angle with respect to the array matrix can be used to provide additional information on exact locations of the structures,

particularly damaged sites. For further clarification, a very shallow angle lap with respect to the chip surface provides a magnification in the vertical direction and with staining, can help clarify substructures. Inspection and documentation at appropriate layers of each of the above sections or deprocessing levels by optical, SEM, SEM-EDS spectra and elemental maps, permits complete understanding of good and damaged areas. Due to its fine control compared to mechanical-chemical sectioning, FIB sections of good and damaged areas provide an additional, more refined view of the structures as needed.

## **Failure Analysis and Fault Isolation**

The initial CCD was received in a nonfunctional condition. The device was subjected to 10 laser shots of increasing energy, at an angle with respect to the surface of the array. The entire die was inspected optically and photographed to identify the array area, controlling poly silicon gates, parallel and serial shift registers as well as the clock, gate drive, and power circuitry. An electrical schematic was derived to help gain an understanding of the device's normal operation. This process also provides background information to assist in exploring how the laser shots created a particular level of damage, either causing local pixel malfunction, row or column problems, combined problems or total device failure.



*Image 1*  
*High magnification photograph of the laser damaged area.*

The chip was removed from its package and then divided in half via diamond sawing. One half was utilized to successfully remove the organic cover-coat, lenses, planarization, metallization, and insulating glass layers to gain access to the underlying

pixel structure. A portion of the other half was subjected to a very shallow angle lap to clarify the gate interconnections and structure of the array. Chemical staining of the pixel area was employed to highlight the subsurface implants and silicon diffusions. The sample with the 10 laser shots was cross-sectioned at 90 degrees successively into several of the laser shots closest to the edge of the chip. Inspection of the laser damaged areas, both optical and SEM provided additional information about the construction of the array. The information obtained from the physical layout, optical and SEM inspections, and SEM-EDS analyses permitted the reconstruction of the active pixel area in the silicon array. Correct placement and alignment of the polysilicon gates, light protecting metallization, dye and lenses confirmed construction of the array elements.

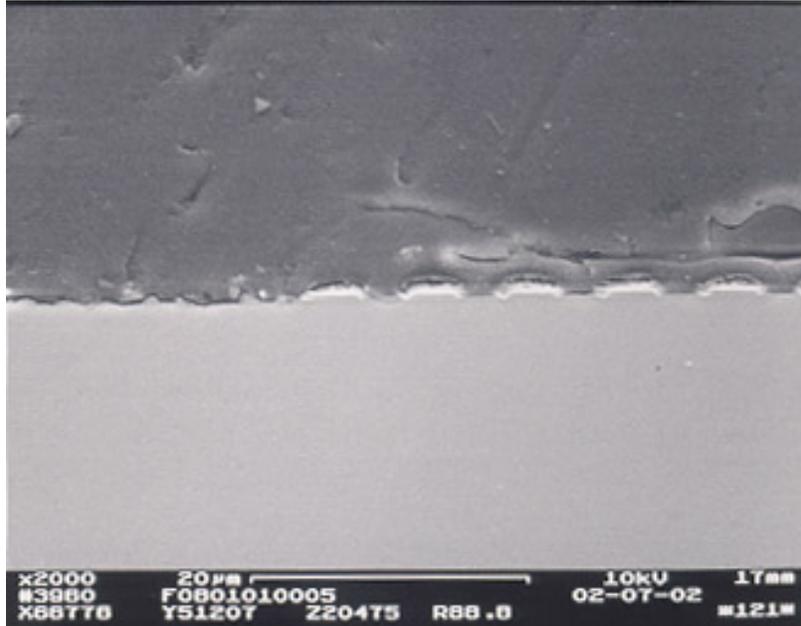


*Image 2*  
*Representative cross section of die structure*

The 90 degree cross-sectioning process of the die was continued into the center of the final laser shot which caused the device failure. Optical, SEM, and SEM-EDS analyses of the sectioned unit in the area of the laser damage and outside the laser shot area, where the device was undamaged, confirmed the hypothesized relationship between the die structures and the pixel sketch showing that the device's array components were as expected.

In the area of the 10<sup>th</sup> shot, the inspections confirmed that the clear coat, planarization layer, lenses, and cover coat had been vaporized. The inspections and analyses also clarified that the dual metal, aluminum over tungsten, light shield had been melted into the polysilicon gates and into the silicon surface shorting the channel stops to the pixels and possibly into the substrate beneath the epitaxial area. The melting of the metal light shield into the silicon is shown on the SEM photomicrographs and SEM-EDS and confirmed by the absence of metal above the polysilicon gates. Damage exhibited at the failure site is typical of the extent of damage that is sufficient to kill a semiconductor

FET. Although no isolation or probe station electrical measurements were made, the metal and polysilicon to substrate shorts were clearly adequate to prevent device operation.



*Image 3*  
*Cross section of laser damage*

Inspection of the laser shots from the top of the array and from the cross sections show the energy distribution of the laser beam shots as they hit the array. The more significant damage was at the center of the shot with less damage moving outward from the center, reaching the edge of the beam where there has been essentially no damage to the organics surrounding the laser shots. The cross section into the 5<sup>th</sup> laser shot shows vaporized and disturbed organics, but intact metallization and polysilicon, confirming that the first 9 shots did not have sufficient energy to melt the light shielding Al-W into the silicon, which would cause complete disruption of functionality. The first 9 laser shots compromised the pixels where the surface organics, dye, planarization layer, lenses and cover coat had been removed or disturbed which would have eliminated the color and light gathering ability of the affected pixels. However, as long as the light shielding metal, polysilicon gates, and inter-metal/poly dielectrics remained intact, the pixels not affected by disturbance or removal of the organics would have (and had) continued to function normally, together with the rest of the device.

FTIR spectroscopy was used to identify that the array cover coat is acrylate polymethylmethacrylate, and using subtraction techniques that the lenses and possibly planarization layer, are Teflon based.

The cyan, magenta, yellow, and green dye over the pixels beneath the lenses had insufficient material to identify their composition. There was a test pattern of the complimentary color and green dye matrix on metal, but the individual dyes were the same size as those over the pixels, preventing the analysis of their individual

compositions. Complementary color dyes are used instead of primary colors so that more light is available to the silicon's pixel photon detectors for increased sensitivity.

A second unit received 36 laser shots of increasing energy in the nano/pico/femto second range. The induced damage was insufficient to cause total failure of the device, allowing for a more detailed investigation of the video output verses the level of damage to the die structure. The laser shots were perpendicular to the surface of the die and had a very narrow diameter, a few pixels, or in some instances, only a single pixel was affected. Approximately 27 of the 36 shots were detectable by optical microscopic inspection. However, the number of damage sites visible when operating, varied from less than 27 to more than 27, depending upon the angle and intensity of the applied light on the array.

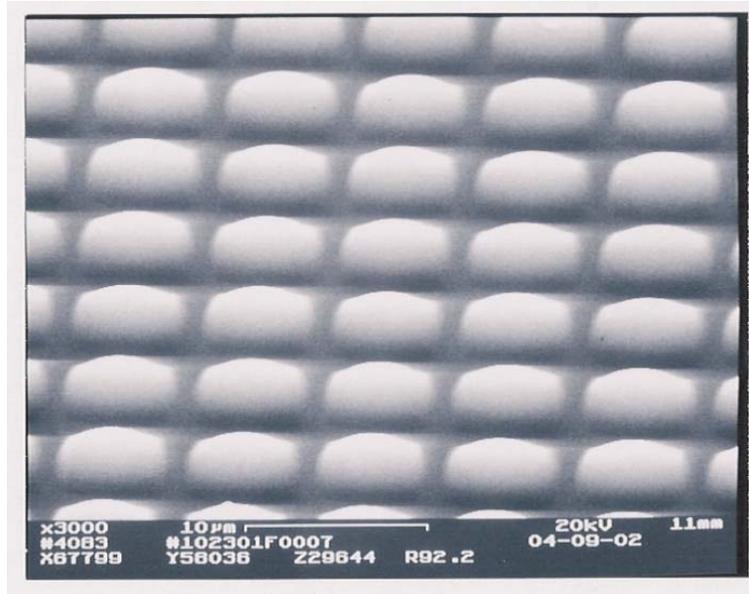


*Image 4*  
*Optical microphotograph of laser shot damage*

Inspection of the damaged spots using high magnification microscopes indicated that the laser had disturbed either the dye, planarization layer, or micro-lens depending on the shot energy of the damaged area inspected. With increasing energy, a corresponding increase in the depth and severity of the disturbance was observed in one or more of the layers. To observe the extent and location of damage it was necessary to continuously vary the focus and mentally reconstruct what was being seen into a three dimensional image. While small sections of metallization could be seen on selected spots, there did not appear to be any significant damage to the metallization.

With a focusing lens attached to the CCD, the camera board produced a nearly normal image, except at the small laser damaged areas. Different colors of light or dark appeared, depending upon which pixels, how many pixels, the amount of dye disturbed, and the amount of damage to the pixels' micro-lens as well as the interpolations of the camera board's image (and pixel) adjusting algorithm electronics.

A small diameter light beam from a high magnification microscope that is co-axial with the optical axis was slowly moved near the edge of the dim, dark, or colored damaged spots. When the light was applied, the damaged spots would output a light level corresponding to or exceeding that of the undamaged pixels around the spots. This confirmed that the damage did not extend down into the metallization, polysilicon, dielectric isolations, or silicon, where the light was being ‘properly’ transformed into an electrical charge. Without the addition of the higher intensity light, damage to the dye, planarization, and lenses deflected, absorbed, or reflected the ‘normal’ light in which undamaged pixel areas functioned correctly.



*Image 5*  
*SEM photo of laser damaged area*

Of interest at the laser damaged spots, visible by optical or functional malfunction, was that SEM secondary and backscatter electron images at various acceleration potentials and at various magnifications were unable to detect any difference in the cover coat or lens shape over the damaged spots compared to undamaged spots. This finding together with the observations made above, confirmed that the damage or disturbance was localized to the organics between the cover coat and the dielectric layer covering the light shielding metallization and silicon. Even the highest energy shot area was indistinguishable from fully functional pixel areas.

A third unit was laser shot 38 times with 24 of them optically visible. The range of energies was in the nano/pico/femto realms. As with the previous units, varying the light type, angle, shading, etc. caused some of the spots that were not operationally visible to become visible. This suggests that the lower energy shots did disturb the organics, but that light perpendicular to the array was not the angle at which the light was attenuated the most.

The first 14 of the 38 shots did not output light when the unit was not illuminated. This was due to the lower energy shots not causing damage down to the silicon, but instead the damage was limited to the organics. In fact, there was so little damage on the first 14 shots, that no evidence of damage could be detected on them with extensive high magnification microscopic inspection in the exact locations of the shots.

The next 24 shots did exhibit light output, even when the unit was not illuminated. This was probably due to the damage reaching the lower portions of the structure, including the dielectric-silicon interface, causing charge injection, which the unit would shift out even when under total dark conditions.

Comparisons of the last 24 shots show an increasing depth of damage and a slight increase in the number of pixels involved. The light or absence of light output, from the damaged areas, also relates to where on the pixel the highest energy of the laser pulse struck, as well as the other factors previously mentioned during discussions of other units.

The device did not exhibit any of the horizontal black lines seen on the previous devices. The main reason for the absence of the black lines is that these laser pulses have a much tighter, narrower energy distribution so that the sides of the damaged areas tend to be vertical rather than sloping as with the broader energy pulses. These narrow laser beams tend to cut the polysilicon gates cleanly and do not short them to adjacent layers of the light shielding metal or substrate, compared to the shallow sided crater cuts with broader energy distributions which were more likely to permit shorting of the polysilicon gates to adjacent conductive layers, causing the horizontal black lines.

Inspection of the highest energy shot 38, which is also, the deepest as seen by comparison of damage depths, indicated that the light shielding metal has melted into the silicon substrate. The metal contact, as with the previous unit that exhibited column blooming, caused the deposition of charge into the column, or columns, in excess of what the gate voltages and electronic shutter could control.

Enlargement of the operating unit's image without light reveals the blooming column either had several columns damaged by the laser shot or that the primary blooming column has sufficient excessive charge to over-ride the channel stops' voltage fields and spill charge into adjacent columns, the left being blue-ish, the right being white-ish. Of interest is that the adjacent columns do not have continuous charge accumulation, along their columns. Rather, the blooming in the adjacent columns appear to have every other pixel 'light' and the ones in between dark, or normal. That phenomenon is most likely due to the way the CCD reads out alternate fields, during which every other vertical pixel is kept 'off' by the gate and the adjacent gate kept 'on' until the next field, after which, the process is reversed.

The vertical transfer of charge is from the bottom to the top of the screen in this image. Thus, the enhancement of the blooming, greater light intensity, and color change of the columns from blue-white-white to green-yellow-orange, is most likely due to a build up of charge as the vertical control gate pump the charge to the horizontal shift register together with affects due to the units control board electronics. If it were due to damaged columns and channel stops, one would expect the phenomenon to be at or near the damage site, which is causing the problem.

Upon closer examination, spots 24 through 38 also exhibit blooming into adjacent pixels but only on the row(s) where the primary pixel damage has occurred. As with the whole column blooming, the single or a few pixels, blooming is most likely due to a local disturbance of the channel stops that lets the charge bleed over into the adjacent column.

As with the other units, operational behavior of the device with a focusing lens produces a normal image over the whole array except in the damage spots and along the blooming column(s).

A fourth device received 11 laser shots, spaced so that there was no overlapping of the rows or columns affected by the damage. This was beneficial for the clarification of damage and allowed for a more definitive failure analysis of the individual shots.

Functional video images from this device produced normal images except in the circular areas of the laser damage. There were three exceptions to this general observation. One shot has one or two dark rows extending from both sides of the spot and becoming less dark the further from the center, until the rows appear the same as those that were fully functional. The highest energy shot produced an essentially identical dark line radiating from both sides of the center crater. In the area of the dark horizontal lines, no video information was obtainable from the related pixels when capturing an image, even though the dark lines did pass information through the dark line. The dark horizontal lines relate to the center of the craters where the highest energy and damage occurred. The damage in the center of the two craters shorted the metallization to the underlying polysilicon gates. Light striking the pixels associated with the dark lines was still causing the generation of hole-electron pairs. However, because the voltage on their related gates was shorted, the electrons were not stored and those pixels appear dark, as if no photons had struck the photo detectors. The relative high resistance of the polysilicon gates, compared to aluminum, permitted the gates in the center of the laser craters to be 'shorted' by metal yet because of their relative high resistance the polysilicon gates away from the craters had sufficient voltage to store electrons from the photon generated hole-electron pairs.

The bright vertical lines originating from the highest energy laser shot, are caused by the vaporization, melting and shorting of the metal light shielding mask through the dielectric and into the silicon of the columns, bounded by channel stops, injecting charge into the columns, causing blooming that masked any hole-electron pair generation and storage in those pixels, preventing them from producing the image from these areas.

The damage craters related to the laser shots on this part exhibit an increasing amount of concave ablation of organic material with the corresponding increase in laser energy.

This unit was also examined using the IR microscope with negative results. However, when this part was examined in the Emission microscope, three of the craters displayed light emission because of the loss of some of the electrons' energy as or after they traversed the damaged oxide. This confirms that the shot had caused damage at least down to the dielectric above the metal and silicon and probably into the silicon. It is interesting to note that one shot did not exhibit any light emission. However, the organic damage could be blocking areas where there are oxide problems shown by the electron energy loss, in the form of light, or that the crater in question did not experience the same

severity of damage to the oxide. It is also interesting that one crater did not exhibit either a black or white line fault. But, that also can be explained by the probability that the energy dissipated in the crater just happened to not involve either the polysilicon gates nor the silicon columns in the same way that the shots did in the other two craters.

Without further analysis, isolation and measurement of the polysilicon gates to other structures, it would be difficult to determine how many gates are involved in the dark lines and how many columns are involved in the light blooming. A single column could be involved, if it had sufficient charge or connection with the channel stops, or several columns could be brighter because of the overflow of charge from the primary column short into adjacent columns.

A fifth unit had received 9 laser shots with energies from the nano/pico/femto realms. When the camera is operated with ambient laboratory light, 2 to 4 of the spots can be seen, depending upon the lighting or shading of the array. The visible spots appear as colored dots of light, or dark spots. With a lens mounted to the device, the rest of the array when in light is fully functional. During operation in complete darkness, four or five of the nine spots were visible in the video output.

Optical inspection of the spots with both low and high magnification microscopes, show different amounts of damage to a varying number of pixels, depending on the energy, time realm, and exact location of the center of the laser shot with respect to the array structure. The video image is affected differently depending upon whether the laser strikes on metal between pixels beneath the lenses, or on the silicon and dye coating, as well as the amount of energy and diameter of the laser beam. Inspection of the remaining spots that did not produce functionally visible anomalies, revealed no optically visible damage. The spots were visible in the video output because the clear coat, lenses, planarization layer and/or dye, had been disturbed sufficiently to cause the laser damage to adversely affect the light path compared to undamaged pixels.

The fact that the damage spots were also visible when the unit was functioned without any light indicates that the laser damage had also disturbed the dielectric-silicon interface or the slightly-sub-surface silicon, so that the damage caused hole-electron pairs to be generated, the electrons accumulated, stored and read out as if photons had impinged those spots.

Because the other 5 spots could not be seen during functional operation, in light or dark environments, nor by high magnification microscopic inspection indicates that those spots did not incur sufficient damage to be detected by the device or its board electronics reconstruction algorithm.

As with the previous units, except the initial killed device, this unit could have polysilicon gates related to the spots checked for resistive shorting by isolation, electrical probing, and measurement related to other structures. This could be followed by appropriate FIB sectioning and FIB-EDS to confirm the location and severity of the damage caused by the laser shots.

A sixth unit received 27 total laser shots with all shots in the nano/pico/femto realm. Operation of the unit with lens showed ~12 shots of varying size and color. Also seen were several adjacent vertical blooming columns that had minor horizontal

blooming, without an image, just at a given level of light. With no light, the horizontal (left) 'light' blooming from the blooming column had two overlapping areas, with the closer area being slightly brighter than the further one.

Finally, a most interesting blooming column(s) was observed that had an operational, image producing section between its lower and upper blooming portions of the column. This is the first column found that did not bloom its full length, preventing any image production from that column. With this column, the bottom  $\frac{1}{4}$  of the column bloomed with a triple of different colored spots at its top. The next  $\sim \frac{1}{3}$  of the column produced an image even though the top 42% continued to bloom. One would expect that with the top portion of the column blooming, which is nearest to the horizontal serial readout shift register, that any signals coming from the operational pixels (between the blooming column) that had to 'pass through' the blooming column to reach the output shift register would be masked by the blooming of the column. However that is clearly not the case.

Initial attempts to explain how this phenomenon could occur were frustrating and frustrated. It caused a re-thinking of exactly how a CCD moved charge from its array to its output and finally to the screen.

Because one sees a constant image from the CCD-board-camera, an impression and conclusion is easily, but mistakenly, made that the charge is not being read out in frames with the electronic shutter acquiring photons for a fixed time period. However, the reason the CCD does read an image from the middle operative length between the column blooming at each end is that the blooming has not consumed the column. There is a lesser charge level than fully blooming columns, which permits the pixels in the middle between the blooming portions to acquire photons/electrons/images normally. Once the electronic shutter 'closes' and photon/electron acquisition stops, the vertical shift registers move the frame of pixels, row by row, into the horizontal shift register and output. Thus, the operative pixels in the column do not really have to move through the blooming column to reach the horizontal register and output.

What is interesting, is how the signal from pixels on the opposite side of the horizontal shift register read their signals out, the same mechanism is operative. However, the more common full blooming columns had confused the issue since they had sufficient damage and enough charge to overwhelm all of the pixels in the column.

Several additional anomalous phenomena were observed when watching the image produced during CCD operation and light conditions varied with the view or the unit was pointed at an even field of light that was then decreased till no light reached the array. The fully blooming multiple columns had sufficient damage to spill into adjacent columns and increase the length of blooming in the adjacent columns with increased light intensity on the array. There was also a translucent appearing lateral 'waterfall' to the left of those columns with ambient light. However, with no light reaching the array the translucent 'waterfall' becomes much more visible, although it was still not bright and the single one that was slightly visible in ambient light becomes two, one overlapping the other.

A seventh unit received 9 laser shots in the nano/pico/femto realm. The 9<sup>th</sup> shot caused the part to become non-functional. DC measurements on each of the failed

CCD's pins yielded essentially the same values as the pins of a fully functional device. The failed and fully functional CCD's were removed from their control electronics boards and switched to the other CCD's board. The failed CCD remained non-functional giving the same no output as it had on its initial board. The units were returned to their own boards and again, as expected, the failed CCD provided no output and the fully functional CCD again was fully functional confirming that the control electronics were not involved in the CCD's failure.

Optical microscopic inspection of the 9 shots confirmed that the damage on the CCD increased with each increase in laser energy. High magnification inspection of the 5<sup>th</sup> shot showed that the spot had damage similar but greater in depth than that of the last shot on T0002 which had vertical column blooming. SEM/SEM-EDS inspection of previous damage on other failed parts indicated that the laser had vaporized the organics and melted the light shielding metallization into the substrate as well as melting the silicon photo detectors to the underlying silicon and channel stops. The level of damage was sufficient to prevent the operation of the device by essentially shorting the light shielding metallization, polysilicon gates, photo detectors, substrate implant, P-well, P+ channel stops, and N substrate which reduced on-chip voltages to ineffective/inoperative levels.

Confirming the failure and determining the exact cause of failure at spot 9 would be accomplished by isolating the polysilicon gates related to the damage area, and electrically microprobing from them and the light shielding metallization to the on-chip gate outputs, on-board bias generator, substrate and power supplies. The DC voltage levels of the failed and fully functional CCD pins indicate that the control electronic board voltages were still functional. Complete verification that was the case would be done by measuring the failed and functional CCD pins with an oscilloscope with sufficient digital memory depth to confirm that the control board electronics signal levels and waveforms were the same.

Further analysis that would provide additional confirmation would be SEM, SEM-EDS spectra and elemental maps of spot 5 and spot 4. And, FIB followed by organic plasma etching, silicon decoration, and SEM, SEM-EDS of both 'kill' spot 5 and 'non-kill' spot 4, for comparison.

An eighth part has 4 types of anomalies from the laser shots. It is interesting that all 16 shots can be seen on the video output of the device when the array receives no light. And, that 11 to maybe 13 are visible when the device is operated in the light. As with the previous units, variations in light and shading on the operating device caused changes in the appearance of the spots and also caused changes in the green waterfalls.

Several of the types of damage have been seen and explained on previous devices. The 3 black horizontal lines, with a white line above and below the dark lines have been previously discussed. Here, the damage is a bit more severe, covering a greater number of gate sets, which most likely gives rise to the 'bracketing' white lines. Additional work will be necessary to properly address the cause of the white lines. However, it could well be an artifact of the decoding circuitry algorithm of the CCDs control board electronics.

The 16/11-13 ('small') spots down the left hand side of the device are related to previous spot damage and the several different spots can be explained with a bit of

additional information. The vertically elongated spots with the unit under both dark and light conditions are a bit different than the other spots on this part and on previous parts. But, it is really a matter of degree. Here the longer vertical spots have damaged more pixels vertically than previous damage spots, thus, they appear as streaks instead of spots. Optical low and high magnification microscopic inspection of the 5 greater elongated spots confirmed that the laser damage with larger circular area at increased energy, corresponded to the greater vertical, and horizontal, number of pixels that were damaged, hence the length and width of the line.

Viewing the video of the unit taken after the laser shots, with the filter in place, the 3 black lines appear white and there is a very narrow [probably a single column instead of the multiple columns seen on the other units] vertical column blooming from the 2<sup>nd</sup> large spot down to the bottom of the screen. There is also a 'split' narrow [single column] blooming column associated with the 5<sup>th</sup> large spot. Neither of the column bloomings were as clearly seen when the unit was operated and its output recorded at Crane. The single columns were occasionally visible, but just for a short time. Thus, the lighting conditions, intensity, wavelength, angle, presence of filter, and lens determined whether and how visible the two blooming columns were when the device was operated.

An inspection of the optical photomicrographs of laser shots numbered 1 and 5 indicate that the damage to the device was from the light shielding metal melting down to the substrate, or damage to the dielectric-silicon interface, silicon of adjacent (vertical) pixels, and local damage to channel stops so charge could spill to adjacent columns but only for a portion of the column.

The green 'waterfalls' do not prevent images from 'beneath' them from reaching the horizontal serial output register that is at the top of the image. That is clearly seen when the unit was operated with the blue filter and focusing lens reinstalled on the device and images of the lab were taken. The images in the green waterfalls are blurry and somewhat distorted but can easily be recognized. And, with the unit with blue filter and focusing lens removed, placed in a micro probe station and a tungsten probe moved over the array into the second waterfall, again, the probe is slightly blurry but easily seen. In both cases, whether views of the lab and the position of the probe, the acquired image [pixel charges] of the probe had to traverse the waterfalls and the dark row lines to reach the horizontal output serial register, which is at the top of the image with its output on the left, and visible on the video monitor.

The size of the damage corresponded to the energy level of the laser shots. Thus, we are left to explain the 5 'long' vertical white-yellow-black outlined shots and the 3 green waterfalls and should probably address the apparent discontinuities in the bottom two black lines within several spots along the green waterfalls.

- The waterfall effect was created due to decreased gate voltages and stray substrate.
- The charge transfer efficiency is decreased. However, pixels within and outside the waterfall are receiving the same amount of charge.
- Shorting the gate or cover metal to the charge well caused white vertical lines, which creates an overload of charge that the CCD cannot handle, thus the blooming effect occurs.
- Notice that areas between the light lines were still behaving properly due to channel stops remaining intact.

- Failure modes are typically a result of the depth of damage caused by a specific laser shot and the laser's exact location in a pixel/group of pixels.
- The diameter, location, focus, and energy of the laser beam are also critical.

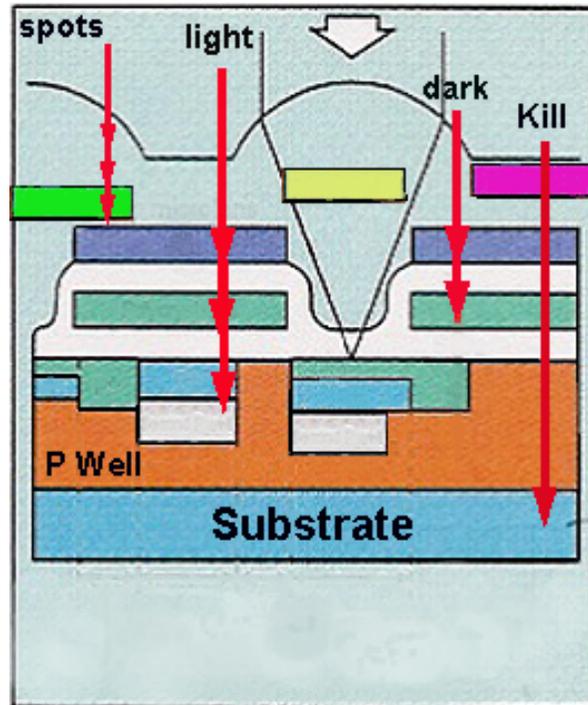


Figure 1

Figure 1 above highlights some of the locations/positions of the laser shot within a pixel (or group of pixels) and which layers/surfaces are damaged or shorted to the next underlying (or adjacent) layer cause the damage seen on the video output.

## Summary of Failure Theories

### Theories of Failure

Once the cell structure, array, chip schematic, on-chip circuitry, physical layout, and drives/controls/algorithms/output controls from the PWB controller are known, the video output of a functional and an anomalous CCDs response to light and dark can be analyzed. Failure theories are established, refined, and confirmed by looking at many different data streams, including, but not limited to the following:

- Electrical measurements and characterization of the device
- Visual CCD-board output (video screen) responses to the laser shots

- Measured and visual response to zero light, low through high level microscope and laser light, etc.
- Knowledge of laser spot size, shape, energy, time range, (and wavelength) per damage site
- Understanding of individual damage sites via selected optical microscope(s) and various mode and light exposures
- SEM inspection, including SEM-EDS spectra and elemental maps,
- Layer by layer deprocessing of the array
- Cross sectioning of the various damage sites
- Shallow angle lap with decoration/staining
- FIB cross-sections in vertical, horizontal, and 45 degrees of characterized damage and undamaged sites, if available
- Emission microscopy of failure sites
- Scanning capacitance probe
- Other analytical method outputs as appropriate

Literature, seminal and other textbooks, manufacturer's part data, university, and research web sites and patent searches augmented CCD cell structures, lenses, circuitry, and operation. Combined with the data listed above, failure hypotheses were devised for the cause of the anomalous behavior. With the hypotheses and theories thus devised, methods to test, refine, refute, or prove the theories can be devised. Methods include duplication or simulation of the failure by physical, mechanical microprobe, laser, light or chemical methods on functional units.

### **Explanation of Chip Failure due to the 10<sup>th</sup> shot**

- SEM results showed that metal and poly had been vaporized and melted to the substrate at the center of the damage area.
- Extent of damage caused a low resistance short of metal to the gates, the substrate implant (n-) and p- and p+ channel stops.
- The short pulls the gate voltages down to ineffective and inoperative values.
- Shorting of the implants and diffusions loads the power to the unit disturbing (lowering) their values and preventing device operation.
- Vertical shift gates, horizontal and output sense amplifiers are inoperative.
- Concentration of varying degrees of light on laser spots causes dark spots to "disappear" on video output.
- Indicates that damage is limited to dye and lens material, not underlying glass/metal/gate structures. Hypothesis: energy wavelength did not disturb overcoat layer and instead damaged dye and lens material underneath. The overcoat layer acts as a barrier to viewing damage when using SEM.

### **Horizontal dark lines adjacent to and on each side of laser spots 8 & 11**

- Radiate along a gate or two for some distance and are darker at the damage circle and lighten further away from the damage area until normal function resumes as the operating voltage gets closer to normal levels.
- The 4 phase poly gates are powered from each end of the array and are individually continuous.

-Dark lines of the gate polysilicon shorted at the damage circle run perpendicular to the channel stops and cross some 30 to 50 channel stops (which define the vertical serial shift register width and thus pixel width).

### **Explanation of dark lines on CCD output**

- Laser energy melted metal to the underlying poly gates causing a resistive short within the damage area (poly gate is more resistive than aluminum).
- Thus, with applied power to both ends of a resistively shorted gate(s), a variation in the dark line (darkest at the damage circle) is expected.
- Can verify this theory by isolating gates and performing curve tracer measurements from the 4 phase gates to ground and the 3 power pins.

### **Explanation of lighted column**

- Emission Microscope results indicate that emitted light was at a higher level on spot 8 than any other spot (also hit with the most laser energy).
- SEM photos indicate significant metal damage (center of damage area - worse than other spots).
- Spot 8 also exhibited "dark line" damage.
- Damage suggests that the metal and poly gates have been melted into one or more of the vertical serial register columns.
- Metal and gate(s) are making electrical contact with the n- and p- (and probably p+) channel stops that define the column(s).
- Voltage on the cover metal or gates therefore is resistively shorted to the substrate in the affected vertical shift registers defined by the channel stops.
- The cover metal or gate voltages cause charge injection in the affected vertical shift registers at the damaged area so that the column's pixel signals all appear to have accumulated a significant amount of light greater than the rest of the array.