Back-Illuminated Wafer-Scale CCD Imager*

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Abstract

We have developed a 1960×2560-pixel frame-transfer CCD which occupies an entire 100-mm silicon wafer and has approximately 10% greater active area than the largest heretofore announced CCD.[1] Figure 1 depicts the structure of the device, showing a split-frame-transfer format with half of the image clocked upward and half downward into frame stores. Each of the four frame stores has an output circuit at both ends of the serial register for a total of 8 outputs. Pixel sizes are 24 μm square in the imaging section and 12×18 μm in the frame store. Well capacity is set by the frame-store pixels and is approximately 80,000 e- in the first lots, but no attempt has been made yet to improve this value. The output circuits have a 3 dB bandwidth of 7 MHz and responsivity of 8-10 μV/e-.

This device has been fabricated with a triple-poly, three-phase process on 100-mm, 20-μm-thick p/p$^+$ epitaxial silicon wafers. In our class 10 fabrication facility we obtain basic yields (gross defects such as shorted gates, etc.) that average about 64%. We have made back-illuminated versions of this device which are optimized for visible-band imaging. The back-surface passivation is done with a boron implant activated by a pulsed laser anneal[2], and with a single-layer SiO antireflection coating we have achieved quantum efficiencies in excess of 80% in the 500-750 nm band. The device is flat to within 10 μm after thinning.

Since conventional integrated-circuit packages are not available for a device of this size, we developed a novel custom package consisting of a molybdenum (chosen for its good CTE match to silicon) plate to which the chip is bonded and a multi-layer printed circuit board which surrounds the chip and is bolted to the plate. All electrical leads are brought onto the board via standard multipin connectors, and the CCD is wire-bonded to Au-plated traces on the PC board. The PC board allows a number useful features to be incorporated such as ESD protection circuitry, video buffer circuits, and temperature sensors.

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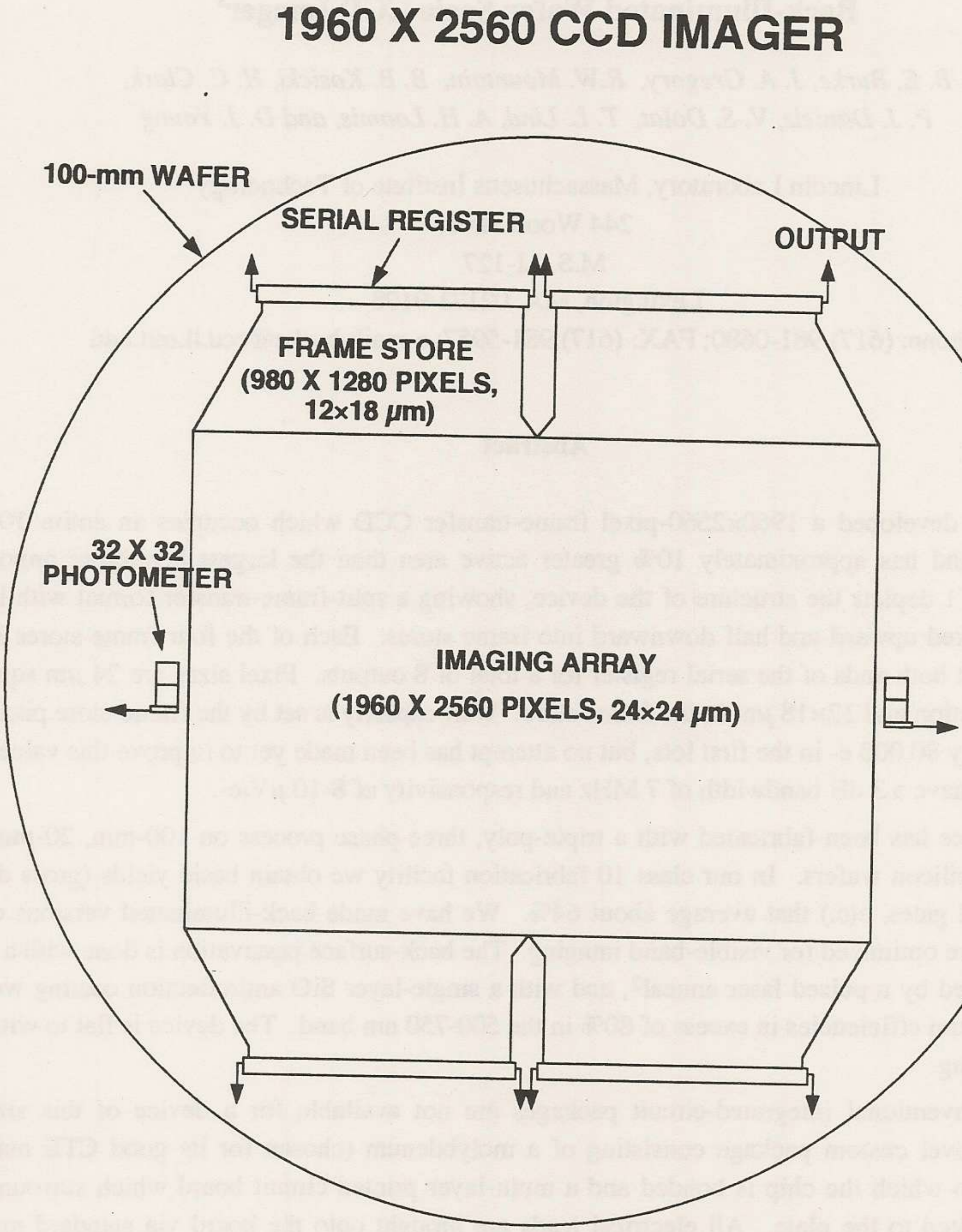
1960 X 2560 CCD IMAGER
100-mm WAFER
SERIAL REGISTER
OUTPUT
FRAME STORE
(980 X 1280 PIXELS,
12×18 μm)
32 X 32
PHOTOMETER
IMAGING ARRAY
(1960 X 2560 PIXELS, 24×24 μm)

Figure 1

Large Area High Resolution CCD Imaging Devices

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Abstract

This paper summarizes rapid progress made in the past few years in the development of large area scientific imaging arrays. CCD imaging arrays from 3cm x 3cm (2048x2048 pixels) to 8cm x 8cm (9k x 9k pixels), will be described. These devices show exciting promise in a variety of medical, astronomical, and high resolution commercial imaging applications.

Introduction

Silicon processing technology has made tremendous strides over the past 30 years. Bipolar transistors were fabricated on 1.5" silicon wafers in production during the late 60's. By the early 70's a stable MOS process had been established and wafers had moved to 2" and 3" in diameter. Boyle and Smith of Bell Laboratories described and demonstrated working Charge Coupled Devices in 1970[1,2]. They are elegantly simple devices which manipulate signals as small packets of charge from one area to another across the silicon surface. An array of MOS capacitors are fabricated over the silicon. The discrete packets of charge are coupled from one capacitor to the next by alternately clocking voltages from one capacitor gate to the next. For scientific applications the signal packets are as small as only a few electrons. During the 70's the quality of the silicon starting material, process chemicals and laboratory cleanliness had not matured adequately to fabricate devices larger than several millimeters on a side. Imaging arrays of 380x488 pixels demonstrated good high level performance, but showed significant signal trapping and fixed pattern noise at signal levels less than 1000 electrons[3].

During the seventies CCD's were proposed to fulfill a variety of functions ranging from analog memories, adaptive filters, radar signal processors, and imaging devices. The mainstream of silicon processing proceeded rapidly pushing the technology in digital CMOS and DRAMS. Production wafers moved from 3" to 4" to 5" to 6", until present day where Intel, Motorola and the rest of the world's major facilities are utilizing 8" wafers for production. Costs of such facilities now cost over $1 Billion and can only be sustained by very high volumes. Digital devices have taken over the potential CCD applications of signal processing and memory. CCDs remain dominant for imaging applications. They provide a small size, low power, and high sensitivity replacement to vidicon tubes. Sony and other vendors routinely manufacture over a million high quality color CCDs per month for use in camcorders. The improvement in process technology now makes it possible to fabricate very large area arrays.

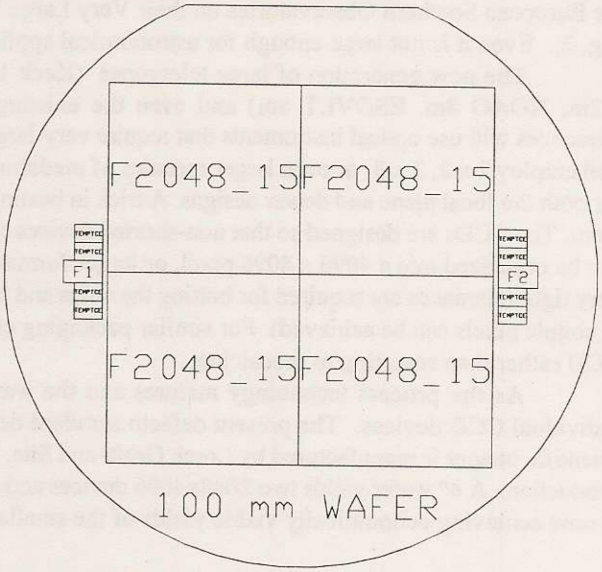

Figure 1 Four Devices per four inch wafer.

**** Note: A version of this paper will be presented at the IS&T Conference "Imaging on the Information Superhighway" May 1995 WashDC.**

Arrays as large as 3 centimeters on a side (2048x2048 pixels) were demonstrated in the late 80's[4]. Those initial imagers were designed with a pixel size of 15µm. sq. specifically to fit 4 devices per 4"(100mm) wafer, Fig. 1. CCD's have one of the largest active gate areas of any semiconductor device. Creating a design which is tolerant to predominant process defects is the key to yields for devices of this size. As a result, process yields are reaching a point where full wafer imagers are not only possible, but becoming economically feasible. The evolution of process technology continues to drive down the price of devices while improving the quality. In the next three sections we describe how large area scientific imagers have become the dominant digital imaging technology.

High Resolution Astronomical Imaging

Astronomers, were the first to recognize the potential of the CCD for high quality scientific imaging. In comparison to photographic film and SEC vidicon tubes originally used, CCDs offer several benefits to the astronomer. CCDs provide long term stability and a direct digital output allowing for very rapid data reduction. With a sensitivity of 100 times faster than film, it is clear that more data can be produced in a shorter period of time. Within a few years the CCD has become the sensor of choice at all major observatories (with the possible exceptions of Schmidt telescopes which utilize very large photographic plates).

Over the past five years Loral has produced a wide variety of custom scientific imagers for Astronomical applications. The majority incorporate 15 micron square pixels. These include 4000x200, 3000x1536, 3072x1024, 2688x512, 2560x256, and 1200x800 configurations for spectroscopic applications. There are variations of a 2048x2048 imager. Versions incorporate provisions for two adjacent side abutting or three side abutting[5,6]. One variation has four outputs, one at each corner of the imager. Two outputs are low noise "skipper" outputs and the other two are standard low noise outputs (3-5 electrons). 24 micron pixel imagers have been produced in 2048x1024 and 2048x2048 configurations. The 2048x2048 24µm imager is a full wafer device which includes on the chip four outrigger startrackers of 200x800 and 200x400 pixels. This chip is for use by the European Southern Observatories on their Very Large Telescope, Fig. 2.. Even it is not large enough for astronomical applications.

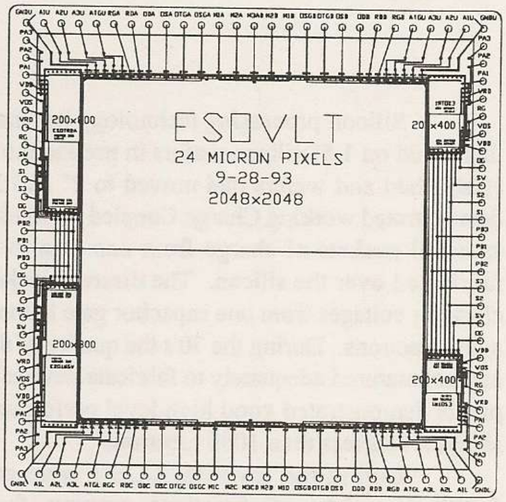

Figure 2 ESO VLT Imaging Array.

The new generation of large telescopes (Keck 10m, JNLT 8.2m, NOAO 8m, ESOVLT 8m) and even the existing 4m class telescopes will use optical instruments that require very-large-format CCD arrays. Many of these proposed instruments will employ 2 x 2, 3 x 3, or even larger mosaics of medium-to-large format CCDs, which present technical challenges for both the focal plane and dewar designs. A trick in beating the yield problem and obtain ultra-large CCDs is to mosaic them. The CCDs are designed so that non-shorted devices can be diced, butted, and mosaiced on two or three edges that can be organized into a 4096 x 4096 pixel, or larger format[7]. Packaging costs are high when using this approach since very tight tolerances are required for butting the chips and keeping the seam regions between each device to a minimum (a couple pixels can be achieved). For similar packaging efforts it may be more cost effective to fabricate a full wafer CCD rather than resorting to mosaicing.

As the process technology matures and the wafer size increases the mosaic consists of larger and larger individual CCD devices. The present defacto standard device is a 2048x4096 15µm three side abuttable array. This scientific imager is manufactured by Loral, Orbit[8] and Site. This is presently the optimum cost/yield tradeoff for pratical production. A 4" wafer yields two 2048x4096 devices and a 5" wafer yields three. Processing quality on100mm wafers is now achieving economically viable yields of the smaller 2048x2048 imagers.

Because of the huge investment involved in the construction of these large ground based telescopes every effort is done to achieve the absolute maximum performance from the CCDs. One of the great advantages of the CCD as a detector is the possibility of achieving extremely high quantum efficiencies over a broad range of wavelengths. The highest sensitivities are achieved by thinning the device and illuminating from the back side. In this manner and in combination with appropriate anti-reflection coatings, it is possible to obtain quantum efficiencies that exceed 90% at the peak[9]. Currently this method of greatest QE enhancement is also the most expensive. Backside thinning is very labor intensive. The many process steps require constant monitoring, exotic equipment in a specialized laboratory and a little black magic. There are also associated costs with the required fanout and custom packaging. There is a loss of yield when thinning arrays which can be quite expensive when working with very large area CCD arrays. Thinning is done on an individual die basis and currently costs in the range of tens of thousands of dollars per device. Typically it requires at least two good frontside devices to achieve one good backside device. A thinned CCD is less than 20 microns thick and quite fragile.

Large Area Medical Imagers

Medical X-ray imaging is another area in which film is rapidly being replaced by large area digital CCD imaging devices. The requirements are similar to astronomy, requiring large dynamic range, high quantum efficiency, low dark current, and stable solid state operation. Medical applications include biological x-ray microscopes, medical x-ray cameras (e.g., spot mammography) and dental x-ray cameras. In particular, a CCD-based filmless imaging system for stereotactic biopsy procedures in mammography has been shown to significantly improve the speed and accuracy of the biopsy[10,11].

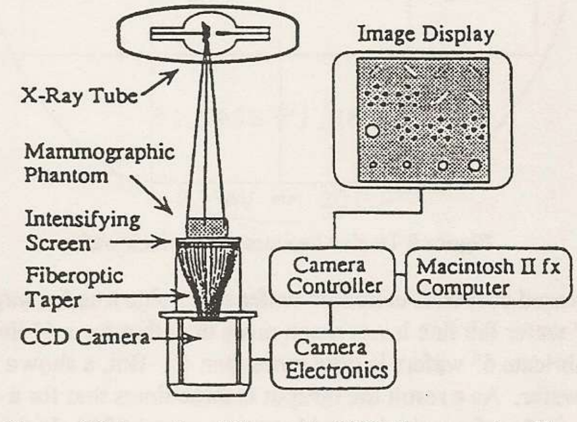

Figure 4 Schematic of fiberoptic CCD X-ray system[12].

Medical X-ray imaging systems typically incorporate a cooled CCD camera system which is optically coupled to an X-ray scintillating plate. The coupling is effected by using either a lens assembly or a fiberoptic plate, Fig. 4. The x-ray beam is converted into light photons by a scintillating screen; then the CCD pixel array samples the optical scene and creates a digital image. The scintillating screen is usually made of a polycrystalline material such as gadolinium oxysulfide or cesium iodide. The transfer of light from the scintillating screen to a CCD imager can be accomplished by direct contact of these components. However, the currently available CCDs are usually not larger than 5cm x 5cm. Therefore a demagnifying optical coupling (either a lens or a fiber taper) must be used between the intensifying screen and the imager in order to cover an area larger than the size of the imager. Initial demonstrations utilized a Loral 2Kx2K CCD imager with an active area of 3cm by 3cm. Recently Loral has delivered a 4Kx4K imager with and active area of 6cm by 6cm. This is sufficient to image a complete biopsy area without requiring a tapered fiberoptic bundle. The scintillator plate may be attached directly to the CCD. Requirements for a full-field, 18cm by 24cm imaging system for mammographic screening and diagnosis will still require a more complex multiple CCD system. Loral is presently under development of a 4Kx4K CCD imager with an active area of 8cm by 8cm, one of the largest CCDs ever produced. It will include special processing techniques to minimize sensitivity to radiation damage.

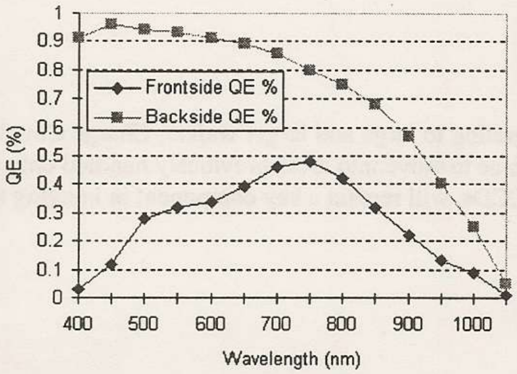

Figure 3 Backside vs Frontside QE.

Smaller X-ray imagers 2.6cm by 3.3cm suitable for intra-oral dental imaging are now being produced in the thousands. A scintillator plate is mounted on the face of the CCD and encapsulated in an autoclavable package for insertion in the mouth. The advantages of an all digital approach over film are similar to those in mammographic applications. A dramatic drop in radiation level is achieved. There is a significant reduction in exposure time and less X-ray neutralization of trauma drugs. The images can be displayed immediately with a wider dynamic range and can be electrically transmitted to a remote site for archival on the information superhighway.

High Resolution Digital Imaging

By the middle 80's the commercial market for camcorders was completely dominated by CCD's. Vidicon tubes common in the first generation cameras had been replaced by the solid state, stable, low power CCD. Higher resolution CCDs are migrating up into the higher end still camera arena as a film replacement. Several Japanese manufacturers now produce high resolution (>1300x1000 pixel) HDTV imagers which are now being seen in still cameras. Minolta and Nikon describe such devices in this conference. In the United States, Leaf and Mega-Vision are producing replacement camera backs for Hasselblad cameras. The camera backs use the Loral 2Kx2K CCD for both monochrome and color operation. Their high cost (>$25K) limits their use to high end commercial photographic applications at this time. As the yields and volumes increase, prices will drop and applications expand.

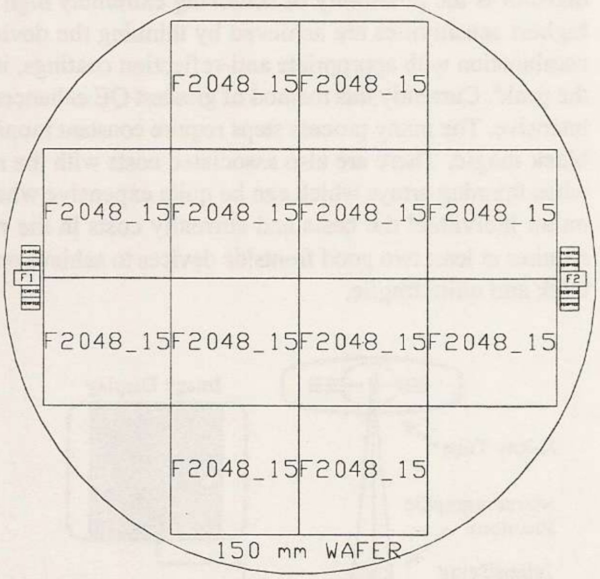

Figure 5 Twelve Devices per six inch wafer

The same philosophy which works for microprocessors and memory chips, increased yield and decreased cost with increased wafer size holds true for large area high resolution CCD imagers. The capital costs for a 6" wafer fab line is not much more than that for a 4" line. The time, manpower, chemical costs and moves required to fabricate 6" wafers is little more than 4". But, a shown in Figure 5, twelve 2Kx2K CCDs are fabricated on a single 6" wafer. As a result the thruput is three times that for a 4" fab line. Presently major semiconductor manufacturers utilize 8" wafers which would contain a total of 21 devices. Of course, if the wafer is bigger someone will want to fill it. There are customers whose applications dictate the largest imager possible and can tolerate the significant cost. And as yields and the technolgy improves full wafer imagers move within the realm of practicality.

A full wafer 5040x5040 element large optical format aerial reconnaissance imager has been demonstrated by Dalsa and fabricated through the foundry at Orbit on 4" wafers.

Loral has fabricated a 4096x4096 15µm, three side buttable, scientific imaging array with satisfactory yields at both Newport Beach and Milpitas. A multi-phase 4096x4096 array has also be fabricated specifically for mammographic applications. The real pièce de résistance is a 9216x9216 pixel imaging array under development at Loral Federal Systems 5" wafer facility in Manassas. This reconnaisance imaging array has an incredible 85 million pixels per frame. With 32 outputs and a readout rate of 2.5 megahertz it will take a full second to readout a frame. Digitized to 12 bits a single frame would occupy 127 million bytes. Clearly an information superhighway is necessary to prevent overwhelming any form of data storage when imaging at a reasonable frame rate. The pixel size is 8.75 µm square forming an image area of 8cm by 8cm. The imager uses a special three layer polysilicon process and optimum design rules to achieve optimum yield.

Conclusion

As semiconductor technology continues to improve, migrating to large and larger wafers, Charge Coupled Devices will keep pace. The use of these imaging devices will continue to move into areas previously handled only by photographic film as costs drop and speed and resolution expand. CCDs. will remain a key component in imaging the visual environment on the Information Superhighway.

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