The Charged-Coupled-Device-Addressed Liquid Crystal Light Valve

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ABSTRACT

The status of the Hughes CCD-addressed liquid crystal light valve is reported in this communication. 256x256 array devices with good output uniformity and full video operations have been demonstrated.

1. INTRODUCTION

Spatial Light Modulators (SLM's) represent a key component in a wide variety of optical systems(1-5). Thus SLM's or, light valves are the main elements in numerous display applications ranging from wrist watches and miniature liquid crystal (LC) devices through flat panel displays to high brightness large projection systems for theaters, teleconferencing and flight simulation applications. In the particular area of head-mounted displays (HMD's) compact image source devices are needed for improving the pilot's visual capabilities as well as in numerous daily activities requiring head-mounted, see-through capabilities such as surgery, auto-mechanical operation, low vision aids or virtual reality displays. Compact SLM's are also critically needed for optical co-processors to perform such operations as spatial filtering, non-linear coordinate transformations, and correlations for robotic applications. Finally, SLM's also find uses in optical interconnects adaptive optics and wavelength image converters. In this paper we describe the marriage of two technologies: charge coupled devices and liquid crystal, to form a compact, high resolution spatial light modulator for the applications above.

Since the introduction of the charge coupled device (CCD) in the early 1970's, it has steadily grown in popularity for several applications. Its most widespread use today is in the area of image sensing. It has many unique features including simple fabrication, low power consumption, high sensitivity with low noise, analog signal capacity with large dynamic range, and high speed operation with a serial output capability.

Some of the features above are also desirable in a display device. Such a device essentially operates in reverse, accepting an electrical input signal and using it to produce an optical image. The key to producing such a device lies in the ability to generate or modulate light in proportion to the charge data that is held in the CCD structure. Since the amount of charge stored in the CCD is relatively small, the most viable approach is to use a light modulator that can be fully activated by the level of charge present in the CCD. Liquid crystals are ideal for this application since they consume very little power and have extremely high electro-optic coefficient i.e., they require very low activation field.

Hughes Research Laboratories (HRL) have previously developed several optical devices that are relevant to this type of application. These devices are known as liquid crystal light valves (6,7) and have been used as image amplifiers or converters. An optical image input to the back side of the device is used to produce a photogenerated charge pattern that activates a liquid crystal light modulating layer on the front side of the device. A secondary light source illuminating this layer can replicate the original image at any wavelength in the visible or infrared spectrum with either coherent or non-coherent beam. This image may be several orders of magnitude brighter than the original image, with minimal degradation in image quality.

If a CCD structure is used to replace the photogenerated charge pattern on the input of the light valve, an image can be produced directly from an electronic input. This eliminates the need to produce an optical input image to the device. The inherent serial/analog nature of the CCD makes it ideal for interfacing directly with video signals with a minimal amount of external circuitry. Since the image is formed directly from the CCD array, the resolution and pixel size are determined by the mask set used in fabricating the device. This eliminates linearity and geometric distortion problems found in CRT displays and also allows precise mechanical registration with respect to the mounting fixture. The built-in-CCD frame-buffer memory makes this device uniquely suitable for coherent optical processing applications as well as for compact displays systems. Finally, this miniature size image source (1000x1000 array is expected to be <2cm x 2cm) is ideal for head-mounted displays.

Past development of this device was previously covered in several publications (8,9). In the following we summarize the recent developments and present status of this device.

2. STRUCTURE AND OPERATION OF THE CCD LCLV

The CCD LCLV is an electrically addressed spatial light modulator that is based on the silicon LCLV technology developed at Hughes Research Laboratories(7). It features a serial electrical input that is converted to a truly parallel optical output. The CCD LCLV can utilize both coherent and incoherent readout light sources, with a spectrum extending from the visible to the infrared.

A schematic of the structure of the CCD LCLV is shown in Fig. 1 A CCD integrated circuit is fabricated on one side of a silicon wafer and is used to supply a spatially resolved signal to the light valve structure on the opposite side. The essential device components are (1) CCD circuits, (2) a readout structure, (3) a dielectric mirror, and (4) a liquid crystal. The CCD circuits convert the serial input voltage signal into sampled charge packets and distribute them into a regular two-dimensional array, which presently configured to be 256x256 pixels. The readout structure transports the charge information from the epitaxial layer, on which the CCDs are built, to the opposite side of the silicon wafer, while retaining the spatial resolution of the charge packets. The dielectric mirror reflects a high percentage of the readout light while greatly attenuating the non-reflected portion in order to prevent activation of the photosensitive silicon substrate. The liquid crystal electro-optic layer converts the charge in each of the packets into a proportional level of modulation of the readout light.

3. DEVICE FABRICATION

Starting with high resistivity material ~ 5KΩ-cm (float zone), 5 cm diameter, 500 µm-thick wafers are first subjected to epitaxial layer growth (5 µm, 5Ω-cm). Following the epi growth the next step is the fabrication of the 4-phase CCD circuits including the input diodes and output amplifiers. Following testing of the CCD processed circuits, the wafers are mounted (CCD-down) for mechanical thin down to ~125 µm. Next the readout structure is processed. This includes the formation of the micro-diode array and the thermal gate oxide growth. Electrical contacts to the CCD circuits are then opened, followed by metalization.

The device assembly is then completed by the deposition of mirror followed by that of liquid crystal layer and the packaging of the structure within a mechanical holder.

The summary of the main processing steps is presented in Table 1.

TABLE 1: CCD LCLV FABRICATION

CCD Section
- Growth of epitaxial layer (5µm, 5 Ω-cm)
- Channel stop (P^+) diffusion
- Implantation of diodes and output amplifier (N^+)
- Two levels of oxides and poly-silicon gates
- Thin down to 125 µm (5 mils)

Readout Section (Front-to-back alignment)
- G-ring and focusing grid implantation
- Gate oxide growth
- Mirror deposition

CCD Section
- Open contacts
- Metallization

CCD LV Assembly
- Wafer mounting and flattening
- Wafer to frame wiring
- LC deposition & counter-electrode mounting

4. RECENT DEVELOPMENTS

The recent developments in this technology include:

(1) the implementation of a novel transfer bonding technique for flat surface mounting
(2) demonstration of live video

(3) demonstration of the use of this device in a dual image/display mode
(4) redesign and start of a refabrication of CCD LCLV device on 4-inch silicon wafers

Finally the use of the CCD LCLV in performing RF spectral analysis was recently demonstrated(13).

5. Present status of the CCD LCLV

The present status of the device is summarized in Table 2.

TABLE 2: CURRENT STATUS OF THE CCD LCLV

- Array size: 256x256
- Active area: 5mm x 5mm
- Limiting resolution: 25 lp/mm (pixel-size-equivalent
- Contrast Ratio: 50:1 (HFE mode)
- Grey-scale capability with real time video
- 30 mSec frame time

CCD Driving Circuitry

- Surface array (SCCD) charge transfer efficiency (C.T.E.) 0.9998/ @ 300 KHz
- Demonstrated up to 200 Hz CCD frame rate (fi 13 MHz serial data rate)
- Demonstrated buried channel (BCCD) operation - 0.99992 C.T.E. @ 3 MHz
- Demonstrated BCCD to SCCD transfer

6. ISSUES AND PLANS

One of the important goals for this device is to scale it up to an array size of ~1000x1000 elements. In order to accomplish this we need to drive the serial input register to frequencies of: $f_{SIR} = 60 \text{ Hz} \times 10^6$. This frequency is on the order of 80 MHz which is beyond the current Si-CCD (buried channel) technology.

In order to accomplish this scale-up we intend to (a) fabricate a buried channel CCD SIR and, (b) to section the SIR and the parallel array into ~2-4 sections each of which will be accessed in parallel. In this way the driving frequency of the SIR will be effectively reduced to ~50 MHz which is well within the bandwidth of BCCD devices. The technique of transferring the signal charge from a buried channel SIR to the surface channel parallel CCD array was previously demonstrated at our laboratory.

The CCD-LCLV fabrication should be simplified in order to accomplish a higher yield and improved resolution. One of the main causes for yield reduction has been the high temperature processing of the readout section. We intend to study the implementation of a Schottky/pN diode readout. This should improve the yield as well as allow a thinning down of the silicon substrate for increased resolution.

Finally, for optical data processing applications a much faster frame rate will be required. In order to accomplish this we will study the use of an increased multiplexing scheme of the input array to allow up to 1 KHz frame rate operation. In order to support a fast liquid crystal response we will examine the use of either the surface mode operation of a nematic LC previously demonstrated with our photoactivated Si-LCLV(14) or, the use of the fast deformed Helix LC mode as suggested by Prof. M. Schadt(15).

7. REFERENCES

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Figure 1. Schematics of the CCD-addressed LCLV

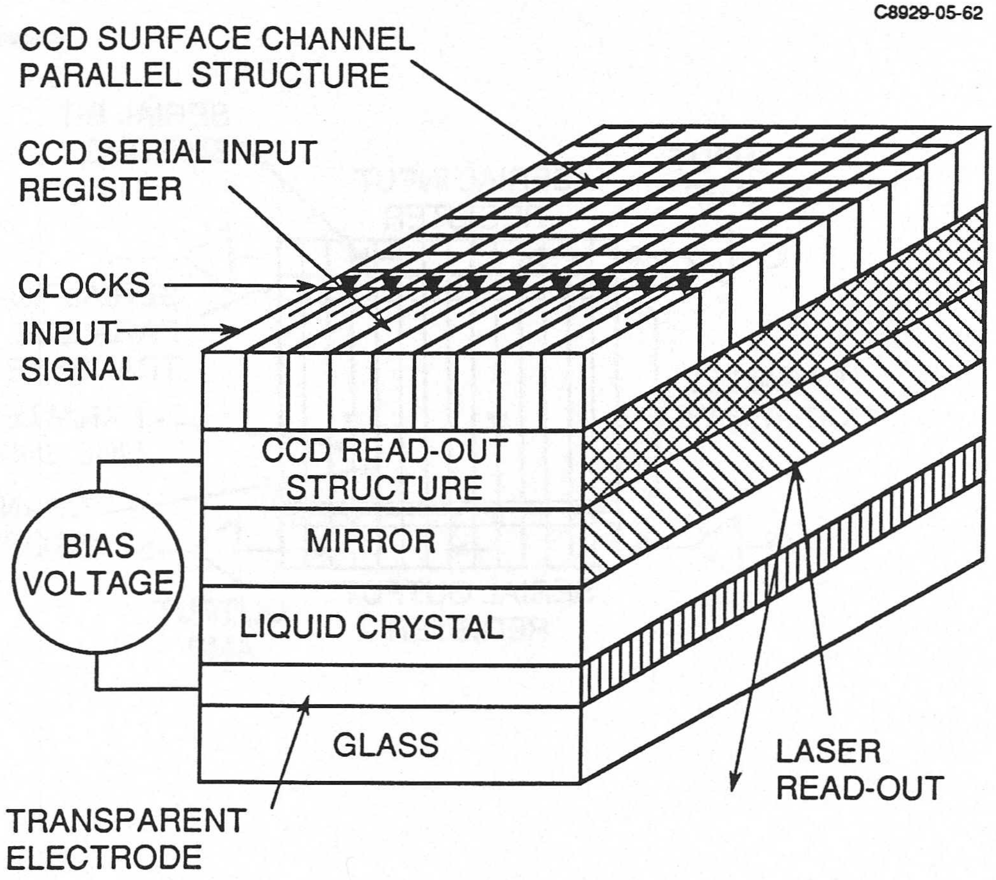
Figure 2. Block diagram of the CCD-circuits

Figure 3. Cross-section of the CCD-LCLV

Figure 4. CCD-LCLV: Transfer bond technique

Figure 5. Live video scenes from "Star Wars" displayed on the CCD LCLV.

Figure 6. A video-formatted output of the 256x256 CCD LCLV used as an imager. The image of three horizontal and two vertical bars are shown.



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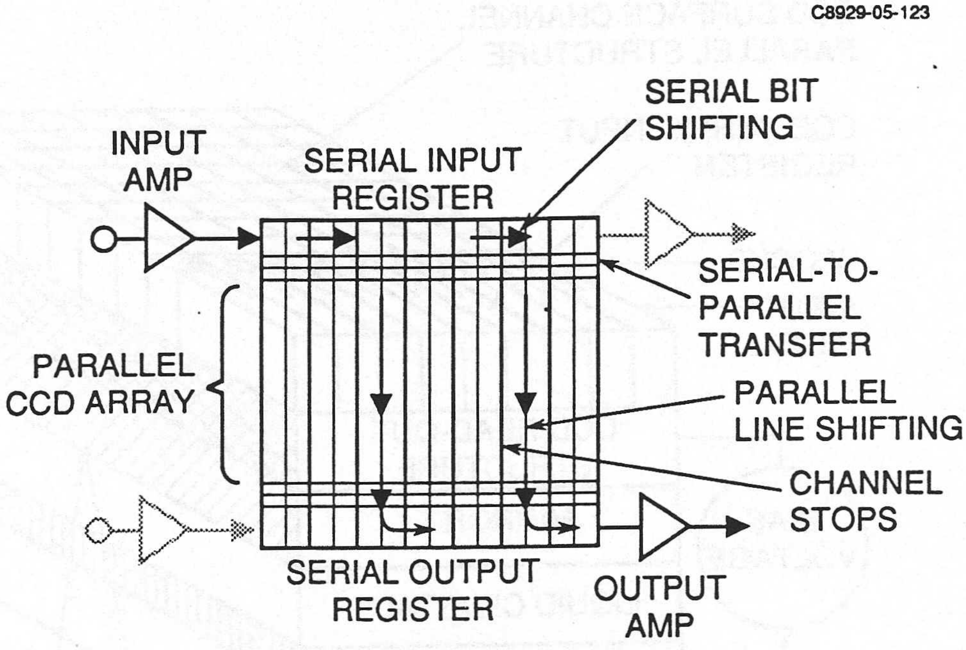

Figure 2. Block diagram of the CCD-circuits

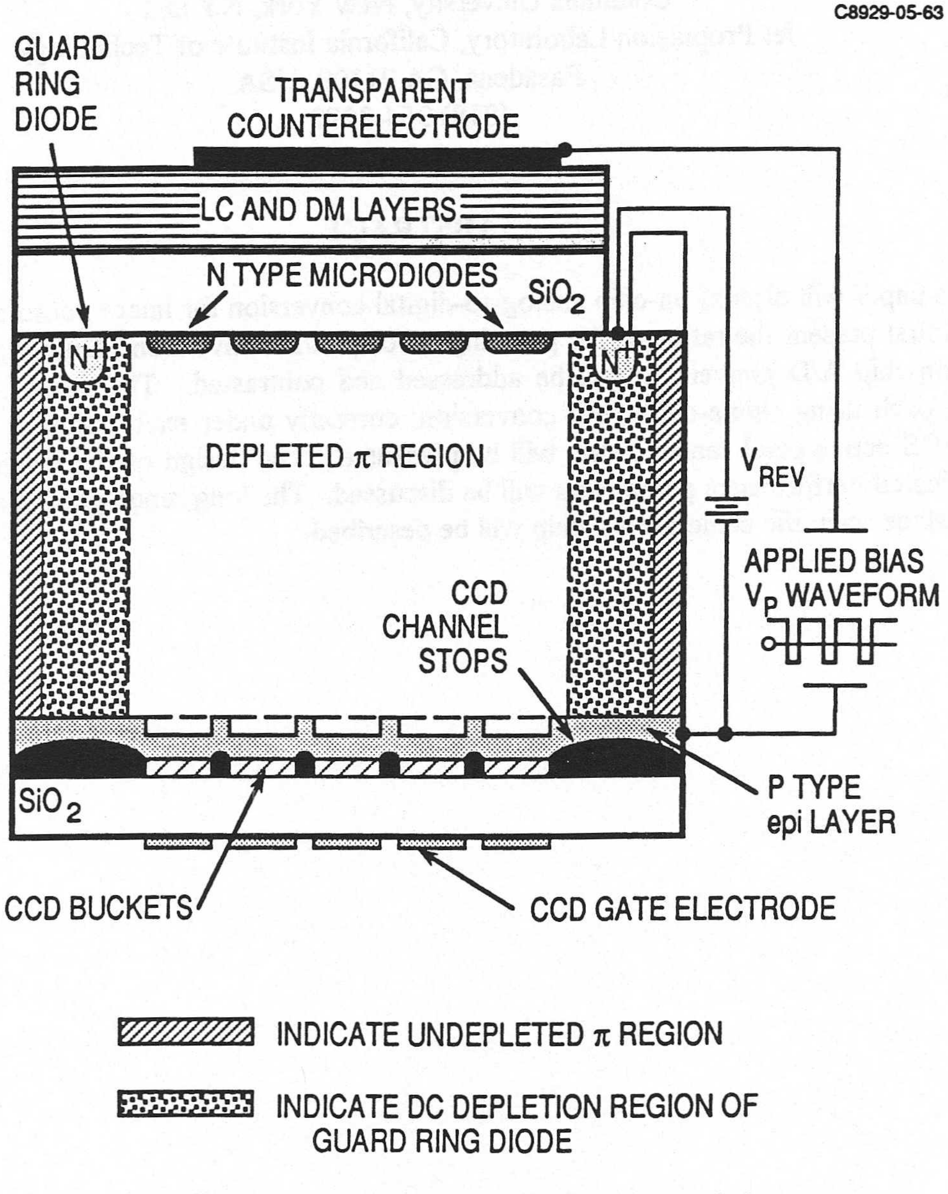

Figure 3. Cross-section of the CCD-LCLV