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SPECIFICATIONS FOR THE
LINEAR CHARGE COUPLED DEVICE
FOR USE IN TRANSIENT RECORDING

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Lawrence
Livermore
Laboratory

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LINEAR CHARGE COUPLED DEVICE
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Joseph W. Balch

ABSTRACT

Specifications are presented for the Linear Charge Coupled Device (LCCD) developed at the Lawrence Livermore National Laboratory for recording data from transients. This device can be used to record electrical signals at sample rates greater than 10^9 samples per second. Both electrical and physical specifications of the device are presented. The bias and drive requirements of the device are presented in tables and in timing diagrams. Typical performance data are tabulated and shown in oscilloscope photos. The physical specifications of the device include plane and cross sectional drawings of its various registers and I/O sections. Enlarged photos of the mask set are shown and all critical dimensions of the active regions are given. Finally, the impurity doping profile used for the transfer channels is shown.

DESCRIPTION OF DEVICE

The LCCD is a Linear Charge Coupled Device type of analog delay line developed for recording high speed transients. Its architecture and design permit transient recording at sample rates of more than 10^9 samples per second. In typical recording of transients, data are loaded into the 640 analog storage cells of the LCCD at a high clock rate. Thermally generated

currents that fill the storage wells with random charge limit the total storage time of the samples in the LCCD to less than 100 milliseconds. Later, the data are read out of the cells at a much slower rate (e.g., 100 kHz) for additional processing by an A/D converter or oscilloscope.

The LCCD consists of five identical input registers, each having 132 storage cells. A schematic of the LCCD is shown in Fig. 1. There is a separate input signal gate for each input register, but all five input structures share a common sample-gate clock. Thus, the LCCD simultaneously samples five separate input signals. The maximum sample rate of each channel is greater than 250×10^6 samples per second. To achieve rates of 10^9 samples per second for a single input signal, the device is used with an off-chip signal splitter and five incremental delay lines to simultaneously sample five delayed replicas of the input signal. By this approach, the LCCD achieves an aggregate sample rate of 1.25×10^9 samples per second when the clock rate is 250 MHz.

The analog data recorded in the device are read out through a single output terminal. The device contains an on-chip multiplexer that recombines the five parallel streams of input data into a single output data stream. The output signal is obtained from an NMOS transistor that is used as a source follower with an off-chip load. Charge detection is done on-chip using a precharged diode connected to the gate of the output transistor. The output structure of the LCCD is designed for low speed operations only, and output data rates are typically 50 kHz to 300 kHz.

LCCDs are packaged in a 40-pin flat pack designed for high bandwidth applications. Figure 2 shows the package and Table 1 lists the pin-out nomenclature.

BIAS AND DRIVE REQUIREMENTS

The normal dc voltages for the LCCD, listed in Table 2, are given with respect to a substrate ground. The dc current requirements for the device are very small. Terminals connected to floating electrodes (ISG, OTG, TG) require less than 1 nA of current, and those connected to reversed biased diodes (ISM, NM, CHS, SK) require less than 20 μ A. The five input diffusions (ID1 through ID5) are reversed biased diodes, but they also provide the electron

charge packets that move down the transfer channels. Their current requirements are typically 10-50 μA . The drain terminal (OD) of the output transistor requires approximately 1 mA of current. To reduce signal distortion and unwanted parasitic noises on the output signal, all dc biased terminals should have by-pass capacitors located near the device, and they should be biased from low impedance sources.

The drive requirements for the several clocks required to operate the LCCD are given in Table 3. The clocks are:

1. A sampling clock (ϕ_{CG}) applied to the five input structures of the device.
2. A two-phase or four-phase clock to transfer charge in the five input registers.
3. A transfer clock (ϕ_{PSG}) to control charge transfer from the five input registers to the single output register.
4. A two-phase or four-phase clock to transfer charge in the output register.
5. A reset clock to precharge the detection diode of the output structure.
6. A clock to drive the buffer gate electrode of the input structures. This terminal may be driven either by a separate clock (ϕ_{BG}) or by phase one of the input register clocks (listed as item 2 above). Better input sampling is obtained if the buffer gate clock is a separate clock, with voltage levels independent of the transfer clocks of the input registers.

The load capacitances of the clock electrodes are given in Table 4. Load capacitances are nonlinear functions of the voltages across the capacitances because voltage dependent depletion regions exist at the silicon surface and in the P-N junctions of the device. The minimum and maximum ranges of the capacitances listed in Table 4 correspond to the minimum and maximum voltages of the applied clocks.

The recommended timing diagrams for the clocks are shown in Fig. 3 for the input registers and in Fig. 4 for the output register. Each storage cell of both the input registers and the output register consists of four adjacent electrodes connected to four separate clock bus lines. The registers can be operated by either four-phase or two-phase clocks. For four-phase clocks, each clock phase should have a 50% duty cycle, and the four clocks should have quadrature phasing with respect to each other. The timing diagram shown in Fig. 4 for the output register demonstrates quadrature phasing.

To operate a shift register with two-phase clocks, the four clock-bus lines of a register are driven in pairs by two clock phases that are 180° out of phase. In addition, a dc bias must be applied between the two electrodes of a given clock phase to create unidirectional flow of charge in the register. Figure 3 demonstrates two-phase clocks for the five input registers.

At the end of the high speed recording interval, the clocks of the input register must switch from their high recording frequency to a much slower readout frequency. This frequency reduction must be done in such a way that the charge samples in adjacent shift register stages remain distinct. In a two-phase clocking scheme, switching requires that one clock phase remains high and the other clock phase remains low throughout the frequency switch-down interval.

PERFORMANCE

The performance of the device is outlined in Table 5. Figure 5 shows a typical pulse response for one of the five input registers when the device is driven by a 200 MHz, two-phase clock. In this photo an output signal of 200 mV is shown for an input signal of 1.5 V. For this photo the device was biased for a bipolar input signal by biasing the input diffusions so that they injected one-half full-well charge packets (200 mV output) into the transfer registers when the input signal was zero.

PHYSICAL SPECIFICATIONS

The overall geometry of the LCCD is shown in the photo of Fig. 6. The device consists of four sections:

1. Five input structures.
2. Five input registers.
3. One output register.
4. A charge detection FET.

The physical layout for the input structures and the high speed transfer registers is shown in Fig. 7. This composite scale drawing shows all the electrodes (BG, IN, ISG, CG) and diffusions (ID1 through ID5) of the five input structures, and transfer electrodes for the input registers ϕ_{11B} , ϕ_{11S} , ϕ_{12B} , and ϕ_{12S} . The physical dimensions for the various electrodes are listed in Table 6. The minimum feature size on the device is 5μ , which is the size of the isolation gate and the transfer electrodes of the input registers.

A cross sectional view of an input structure and the first transfer stage is shown in Fig. 8. The registers are built using buried channel CCD technology, which uses a surface N-layer on a P-type substrate. The 1200 Å dielectric that separates the silicon surface from the polysilicon electrodes consists of 800 Å of silicon dioxide and 400 Å of silicon nitride. Three levels of polysilicon are used for the various electrodes on the device. The doping profile of the N-layer is shown in Fig. 9.

The top and side views of the charge detection FET of the LCCD are shown in Figs. 10 and 11. The active region of the output transistor is an area of the P-type substrate having no ion implantations. However, the output transfer register uses the same N-P doping profile as the input registers. The active dielectric of the output register and output FET also consists of 800 Å of silicon dioxide and 400 Å of silicon nitride.

The mask set used to fabricate the device contains 12 separate masks. Table 7 lists the mask set. Copies of the masks are shown in Figs. 12 to 23 at a magnification of approximately 50 times.

TABLE 1. Pin assignment for an LCCD having 2-Phase input registers.

Pin No.	Symbol	Name
1	ID3	Input diffusion 3
2	ID4	Input diffusion 4
3	IN4	Signal input 4
4	SUB	Substrate
5	ID5	Input diffusion 5
6	IN5	Signal input 5
7	CHS	Channel stop
8	BG	Buffer gate
9	Ø11B	Input register clock Ø1, block
10	Ø11B	Input register clock Ø1, block
11	Ø11S	Input register clock Ø1, storage
12	Ø11S	Input register clock Ø1, storage
13	OPSG	Parallel-serial transfer gate
14	SUB	Substrate
15	Ø04	Output register clock Ø4
16	Ø02	Output register clock Ø2
17	Ø03	Output register clock Ø3
18	Ø01	Output register clock Ø1
19	NM	N-Moat
20	SUB	Substrate
21	OUT	Output signal
22	OD	Output FET drain
23	SK	Sink
24	RG	Reset gate
25	TG	Tetrode gate
26	OTG	Output transfer gate
27	SUB	Substrate
28	Ø12S	Input register clock Ø2, storage
29	Ø12S	Input register clock Ø2, storage
30	Ø12B	Input register clock Ø2, block
31	Ø12B	Input register clock Ø2, block

TABLE 1. (Continued).

Pin No.	Symbol	Name
32	ISM	Isolation moat
33	ØCG	Cutter gate
34	ISG	Isolation gate
35	IN1	Signal input 1
36	ID1	Input diffusion 1
37	SUB	Substrate
38	IN2	Signal input 2
39	ID2	Input diffusion 2
40	IN3	Input signal 3

TABLE 2. Bias voltage requirements.

Symbol	Characteristic	Range of Voltage (V)		
		Min	Typ ($V_{SUB} = \emptyset$)	Max
V_{ID}	Input diffusion voltage	6	13	20
V_{ISG}	Isolation gate voltage	-5	+2	+5
V_{OTG}	Output transfer gate voltage	-5	-2.5	+5
V_{SK}	Output sink voltage	10	16	25
TG	Tetrode gate voltage (Reset FET)	-5	$\emptyset$	+5
V_{OD}	Output FET drain supply	15	20	25
V_{CHS}	Channel stop voltage	$\emptyset$	$\emptyset$	-5
V_{NM}	N-moat voltage	$\emptyset$	$\emptyset$	5
V_{ISM}	Isolation moat	$\emptyset$	$\emptyset$	-5

TABLE 3. Clock drive requirements.

Symbol	Characteristic	Range of Voltage (V)		
		Min	Typ	Max
$V_{\phi ISL}$	Input register storage electrode 2 ϕ clocks low	-10	-5	--
$V_{\phi ISH}$	Input register storage electrode 2 ϕ clocks high	--	5	10
$V_{\phi IBL}$	Input register blocking electrode 2 ϕ clocks low	-15	-10	--
$V_{\phi IBH}$	Input register blocking electrode 2 ϕ clocks high	--	0	5
$V_{\phi PSGL}$	Parallel to serial transfer gate clock low	-15	-9	--
$V_{\phi PSGH}$	Parallel to serial transfer gate clock high	--	--	--
$V_{\phi OL}$	Output register 4 ϕ clocks low	-10	-3	--
$V_{\phi OH}$	Output register 4 ϕ clocks high	--	+10	+15
$V_{\phi CGL}$	Cutter gate clock low	-5	-3	--
$V_{\phi CGH}$	Cutter gate clock high	--	+12	+15
$V_{\phi BGL}$	Buffer gate clock low	-5	-3	--
$V_{\phi BGH}$	Buffer gate clock high	--	+12	+15
$V_{\phi RGL}$	Reset gate clock low	-5	-3	--
$V_{\phi RGH}$	Reset gate clock high	--	0	+5

TABLE 4. Load capacitances of clock electrodes.

Symbol	Characteristic	Range			Units
		Min	Typ	Max	
$C_{\phi Ii}$	Two-phase clock capacitance to substrate of input registers ($i = 1, 2$)	12	--	40	pf ^a
$C_{\phi I1,2}$	Input register inter-phase clock capacitance	6	--	14	pf ^a
C_{CG}	Cutter gate capacitance to substrate	1	1.5	2	pf ^a
$C_{CG,IN}$	Cutter gate capacitance to input signal electrode	0.2	--	0.35	pf ^a
$C_{CG,ISG}$	Cutter gate capacitance to isolation gate	0.06	--	0.14	pf ^a
C_{IN}	Input signal gate capacitance to substrate	1	1.3	2	pf
$C_{IN,BG}$	Signal gate capacitance to buffer gate	0.01	--	0.025	pf ^a
C_{BG}	Buffer gate capacitance to substrate	1	1.5	2	pf
$C_{BG,\phi I2}$	Buffer gate capacitance to $\phi I2$ phase	0.06	--	0.14	pf ^a
$C_{\phi Oi}$	Output register phase capacitance to substrate ($i = 1, 2, 3, 4$)	2	--	6	pf
$C_{\phi Oi,j}$	Output register inter-phase clock capacitance	0.5	--	2.0	pf

^a C_{MAX} occurs for Q_{FW} in all cells.

TABLE 5. LCCD typical performance.

Parameter	Value	Units	Condition	Ref. Fig.
Charge transfer efficiency	0.9996	Per S-R stage	Fat zero = 200 mV Signal = 200 mV $f_{in} = 200 \text{ MHz}$, 2 ϕ , 12 V p-p	5
Thermal generation	<1	mV/ms	Fat zero = $\emptyset$ $f_{out} = 20 \text{ kHz}$	--
Full well output signal	400	mV	$f_{in} = 200 \text{ MHz}$, 2 ϕ $f_{out} = 200 \text{ kHz}$, 4 ϕ	5
Full well input signal	3.0	V	$f_{in} = 200 \text{ MHz}$, 2 ϕ	5
Maximum high speed clock frequency	250	MHz	--	--
Transconductance of output FET	0.125	mmho	--	--
Saturation drain conductance of output FET	8	μmho	--	--

TABLE 6. Dimensions of LCCD components.

Physical dimensions (Active areas)	Nominal device dimension	Tolerance	Units
Gate length, isolation gate	5.0	± 1.5	μ
Gate length, cutter gate	7.0	± 1.5	μ
Gate length, signal gate	6.0	± 1.5	μ
Gate length, buffer gate	7.0	± 1.5	μ
Gate length, clock phase ϕ_{11B}	7.0	± 1.5	μ
Gate length, clock phase ϕ_{11S}	5.0	± 1.5	μ
Gate length, clock phase ϕ_{12B}	7.0	± 1.5	μ
Gate length, clock phase ϕ_{12S}	5.0	± 1.5	μ
Channel width, input registers	16.0	± 2.0	μ
Channel width, output registers	26.0	± 2.0	μ
Gate length, parallel - serial transfer gate	9.5	± 1.5	μ
Gate length, clock phase ϕ_{01}	7.5	± 1.5	μ
Gate length, clock phase ϕ_{02}	9.5	± 1.5	μ
Gate length, clock phase ϕ_{03}	7.5	± 1.5	μ
Gate length, clock phase ϕ_{04}	9.5	± 1.5	μ
Gate length, output gate	7.5	± 1.5	μ
Gate length, tetrode gate	7.5	± 1.5	μ
Gate length, reset gate	8.5	± 1.5	μ
Gate length, output FET	10.0	± 1.5	μ
Gate width, output FET	21.5	± 1.5	μ
Thin channel dielectric thickness	1200	± 100	A
Isolation dielectric thickness between polysilicon electrodes	3000	± 300	A
Field dielectric thickness	15,000	± 1500	A
Polysilicon thickness	6000	± 1500	A

TABLE 7. Mask set used for LCCD.

Mask	Shown in	Function
LCCD- 1	Fig. 12	N-Channel implant mask
LCCD- 2	Fig. 13	Channel stop mask
LCCD- 3	Fig. 14	N-Moat mask
LCCD- 4	Fig. 15	Channel window mask
LCCD- 5	Fig. 16	Channel nitride mask
LCCD- 6	Fig. 17	1st polysilicon mask
LCCD- 7	Fig. 18	2nd polysilicon mask
LCCD-10	Fig. 19	3rd polysilicon mask
LCCD-11	Fig. 20	N+ I/O diffusion mask
LCCD-12	Fig. 21	Contact window mask
LCCD-13	Fig. 22	Metal mask
LCCD-14	Fig. 23	Bond pad window mask

FIG. 1. Schematic of LCCD.

FIG. 3. Input timing using two-phase clocks.

Note: The vertical clocks should run continuously to avoid any transients in output waveform at switchdown.

FIG. 4. Readout timing using four-phase clocks.

FIG. 5. (a) Typical pulse response of a single transfer register operated at a two-phase input clock frequency of 200 MHz and a four-phase readout clock frequency of 200 kHz. Vertical scale: 100 mV/division; horizontal scale: 100 μ s/division. (b) Input signal to LCD. Vertical scale: 1 V/division; horizontal scale: 20 ns/division.

FIG. 6. Photomicrograph of the LCCD showing five identical input registers, each 132 stages long, and a multiplexing output register for driving the output charge detection FET.

FIG. 7. Composite drawing of five input structures and input registers.

FIG. 8. The input structure and first stage of an input transfer register. The 1200 Å dielectric between the transfer electrodes and the silicon surface consists of 800 Å of silicon dioxide and 400 Å of silicon nitride.

FIG. 9. Measured impurity profile for buried channels of LCCD.

FIG. 10. Composite drawing of charge detection FET for the LCCD.

FIG. 11. Cross sectional view of the charge detection FET.

FIG. 12. Mask LCCD-1; N-Channel implant mask.

FIG. 13. Mask LCCD-2; Channel stop mask.

FIG. 14. Mask LCCD-3; N-Moat mask.

FIG. 15. Mask LCCD-4; Channel window mask.

FIG. 16. Mask LCCD-5; Channel nitride mask.

FIG. 17. Mask LCCD-6; First polysilicon mask.

FIG. 18. Mask LCCD-7; Second polysilicon mask.

FIG. 19. Mask LCCD-10; Third polysilicon mask.

The micrograph displays a complex pattern of dark, irregular shapes on a light background, representing the N+ I/O diffusion mask. The pattern is dense and irregular, with various sized features and shapes. A small, distinct square feature is visible near the center. To the right, there is a larger, more complex shape with a small rectangular protrusion. The overall appearance is that of a high-resolution scan of a physical mask.

FIG. 20. Mask LCCD-11; N+ I/O diffusion mask.

Fig. 21. Mask LCCD-12; Contact windows mask.

Fig. 22. Mask LCCD-13; Metal mask.

Fig. 23. Mask LCCD-14; Bond pad windows mask.

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