

Hydrogenated Amorphous-Silicon Photosensor for Optically Addressed High-Speed Spatial Light Modulator

WEN LI, MEMBER, IEEE, ROBERT A. RICE, GARRET MODDEL, MEMBER, IEEE,
LAURA A. PAGANO-STAUFFER, AND MARK A. HANDSCHY

Abstract—A high-speed optically addressed spatial light modulator (OASLM) has been developed which incorporates a hydrogenated amorphous-silicon (a-Si:H) photosensor and a ferroelectric liquid crystal (FLC) modulator. The OASLM exhibits a response time of 155 μ s and a spatial resolution of >33 lp/mm. The capacitance and resistance of both the a-Si:H and FLC have been measured and are shown to strongly influence the response of the device. The characteristics of the a-Si:H photosensor are analyzed and discussed.

I. INTRODUCTION

AN optically addressed spatial light modulator (OASLM) is a real-time optical signal and image processing device. The OASLM which we describe consists of a hydrogenated amorphous-silicon (a-Si:H) thin film as the photosensor and ferroelectric liquid crystal (FLC) as an electrooptic modulating material. In operation, when the a-Si:H is illuminated, it produces a surface charge distribution, creating a spatially varying electric field across the FLC, and modulating the optic axis of the FLC. The output image is then obtained by using a polarized laser beam.

The OASLM has many applications including input/output displays, spatial filtering, incoherent-coherent image conversion, optical crossbar switches, and optical neurocomputing. OASLM's have been demonstrated using a variety of photosensors and modulating materials, as summarized in Table I. The Hughes liquid crystal light valve, for example, uses a CdS photosensor and a nematic liquid crystal modulator, and has a cycle time of 100 ms [1]. Ashley *et al.* have fabricated nematic liquid crystal OASLM's using an a-Si:H photosensor [2], [3]¹ which also has cycle times of 100 ms. The switching speed of

these devices is limited by the use of nematic liquid crystals which usually have switching times of only milliseconds. Although self-electrooptic effect devices (SEED's) have microseconds cycle times, they will probably be limited to small sizes due to power dissipation problems [4]. With the discovery that FLC's have microsecond switching speeds and low power consumption [5], it is now possible to build OASLM's with response times in the microsecond regime. This places substantial demands on the photosensor response. The a-Si:H photodiode meets these demands, as described previously [6].

In this paper, we describe in detail the OASLM fabrication and operation, and review the optical characteristics, which have been presented elsewhere [7]. An equivalent circuit that simulates the electrical characteristics of the device is presented, along with criteria for choosing circuit element values to optimize device performance. The device exhibits a 300- μ s cycle time and a spatial resolution of >33 lp/mm. These and other electrical and optical responses are also described in detail.

II. DEVICE DESCRIPTION AND OPERATION

The configuration of the OASLM is shown in Fig. 1. An a-Si:H photodiode with a p-i-n structure, deposited on a transparent conducting oxide (TCO) coated glass substrate, forms the photosensor. The modulator is a chiral smectic C (SmC*) phase FLC sandwiched between the a-Si:H thin film and another TCO-coated glass. In smectic C phase, the rod shaped FLC molecules form equidistant layers. The layer normal to \hat{z} lies parallel to the surface of the TCO-coated glass and the a-Si:H. The FLC molecule is oriented on a tilt cone with a tilt angle ψ from the layer normal \hat{z} . Rubbed polymer on both the a-Si:H thin film and the TCO glass substrates align the FLC. The two substrates are spaced sufficiently closely that the FLC's intrinsic helical structure is unwound, giving "surface stabilization" [8], [9]. The molecules rotate 2ψ from one state to another, depending on the direction of the applied electric field. The tilt angle of the FLC that we used (SCE9)² is very close to 20.5° at room temper-

Manuscript received December 19, 1988; revised July 31, 1989. The fabrication of the OASLM devices were supported by the U.S. Naval Surface Warfare Center under Small Business Innovation Research Contract N60921-88-C-0088, by the NSF Engineering Research Center under Grant CDR-862236, and by the Colorado Technology Institute. The optical measurements were supported by the AFOSR under Contract AFOSR86-0819.

W. Li, R. A. Rice, and G. Moddel are with the Electrical and Computer Engineering Department and Optoelectronics Computing Systems Center, University of Colorado, Boulder, CO 80309-0425.

L. A. Pagano-Stauffer and M. A. Handschy are with Displaytech, Inc., Boulder, CO 80301.

IEEE Log Number 8931487.

¹In [3], the characteristics of the devices vary significantly with the electrode spacing.

²British Drug House (BDH) Ltd., Broom Road, Poole, BH 12 4NN England.

TABLE I
COMPARISON OF OASLM'S

Device (ref)	Usable Aperture length or diameter(mm)	Resolution at 50% MTF (lp/mm)	Cycle Time (ms)	Optical Switching Energy† pJ
Hughes LCLV[1]	25	16	100	10
Hoechst Celanese [12]	40	38	25	36
a-Si:H/nematic [2] (reflection mode)	38	>35	100	2
a-Si:H/nematic [3] (transmission mode)	38	>25	~ 100	~ 15
a-Si:H/FLC [13]	> 2	---	0.8	6×10^{-5}
a-Si:H/FLC [14]	40	28	0.5	0.2
a-Si:H/FLC [6, 7]	10	> 33	0.3	0.15
Hamamatsu microchannel [15]	16	10	150	0.75
PROM [16]	5.8	5	---	---
SEED [4] Bistable mode	0.5	11	~ 0.001	45
Linear mode	0.5	11	~ 1	125

$$\dagger \text{ Optical switching energy per bit} = \text{intensity} \times \frac{\text{write time}}{(2 \times \text{resolution})^2}$$

The modulation transfer function (MTF) is a measure of the contrast ratio. The cycle time is the sum of the 10% to 90% rise time and the corresponding fall time plus any delay times in the response. The optical switching energy per pixel is chosen for 50% MTF, or the nearest value available.

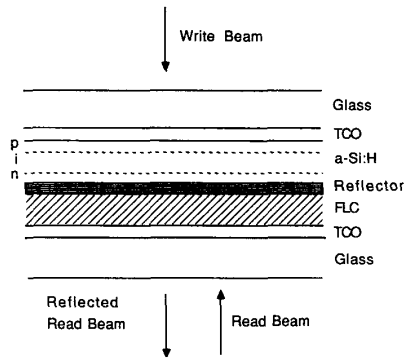


Fig. 1. Optically addressed spatial light modulator (OASLM).

ature allowing the molecules, and therefore the optic axis, to rotate electrically through $\sim 41^\circ$. The device operates in the reflection mode; therefore the read light passes through the FLC twice. The ideal thickness of the FLC layer is chosen so that $2d\Delta n = \lambda/2$ for the reflection mode, where Δn is the birefringence (~ 0.16) and λ is the read light wavelength (633 nm); this produces a switchable half-wave plate for the read light. For the device used, the FLC thickness is $\sim 1.8 \mu\text{m}$, and the active area of the device is $\sim 1.5 \text{ cm}^2$.

For the optical response time measurement, the write light is modulated using an acoustooptic modulator (AOM) with a transition time of less than 160 ns. A delay/pulse generator is used to synchronize the write light and the applied voltage so that the write light is ON only for

a portion of the period when the applied voltage is in the V -period. This sequence allows the measurement of the optical switching time of the device in response to the write light.

An equivalent circuit for the device is depicted in Fig. 2. R_s is the series resistance resulting from the TCO sheet resistance and the a-Si:H bulk resistance, and R_{sh} is the shunt resistance to the leakage current. The capacitance, C_{a-Si} , includes the frequency-independent geometric capacitance and the frequency-dependent p-i-n junction depletion capacitance. R_{FLC} and C_{FLC} refer to the FLC resistance and capacitance, respectively. In later sections, we show that the measured values of R_s and R_{sh} are $160 \Omega\text{-cm}^2$ and $5.3 \times 10^8 \Omega\text{-cm}^2$, respectively. C_{a-Si} is a function of the film thickness and is about 8 nF/cm^2 . R_{FLC} is greater than $20 \text{ M}\Omega\text{-cm}^2$. The C_{FLC} contains two components, a dielectric capacitance of 2 nF/cm^2 and an effective capacitance associated with the ferroelectric polarization which is approximately 3 nF/cm^2 for 25 V dropped across the FLC, as described in [6].

As shown in Fig. 3, the device operates with an applied square-wave voltage. During the forward bias (V_+) part of the cycle, the a-Si:H photodiode is conducting, and therefore insensitive to the write beam. Ideally, the FLC is provided with a uniform positive voltage, and switches completely to one state, defined as the OFF state. This is an erase operation.

Under reverse bias (V_-), the a-Si:H photodiode is not conducting, and ideally little voltage drops across the FLC in the absence of the write light. The FLC remains in the

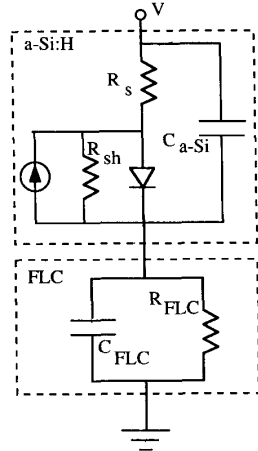


Fig. 2. OASLM equivalent circuit.

OFF state. When the write light is on, the a-Si:H thin film, acting as a photosensor, converts the optical image to a spatially varying electric field across the FLC. Ideally, the FLC switches ON to its other stable state only in those areas corresponding to illumination of the a-Si:H.

There are a number of situations in which the operation of the device departs from ideality. Under forward bias, the a-Si:H conducts, and the voltage drop across the FLC depends on the relative magnitudes of R_{FLC} and R_s as $V_{FLC} = (R_{FLC}/R_{FLC} + R_s) V_+$. When the device is switched to reverse bias, the initial voltage across the FLC is given by

$$V_{FLC} = - \left(\frac{C_{a-Si}}{C_{a-Si} + C_{FLC}} \right) V_{pp} + \frac{R_{FLC}}{R_{FLC} + R_s} V_+$$

and at steady state approaches

$$V_{FLC} = - \frac{R_{FLC}}{R_{FLC} + R_{sh}} V_-$$

when the photodiode is not illuminated. $V_{pp} = V_- + V_+$ refers to the peak-to-peak applied voltage. For a quantitative measure of $C_{a-Si:H}$, it is necessary to determine the amount of collected charge for the a-Si:H thin film as a function of square-wave voltage frequency, as well as the a-Si:H I - V characteristics. Studies of these characteristics are outlined in the following sections.

To reduce the likelihood of the device turning ON without the write light, R_s should be made as small as possible compared to R_{FLC} , driving V_{FLC} to nearly V_+ while under forward bias. This helps to minimize the amount of negative bias across the FLC during the reverse bias transient. Additionally, if R_{sh} is very large compared to R_{FLC} , the steady state value of V_{FLC} under reverse bias is driven toward zero, further reducing the chance of switching ON the FLC while the write light is OFF. Spurious switching of the device also can be caused by the capacitances which divide V_{pp} as shown above. For a symmetric wave, if $C_{a-Si} > C_{FLC}$, a negative voltage appears across the FLC and may switch it to the ON condition even without the

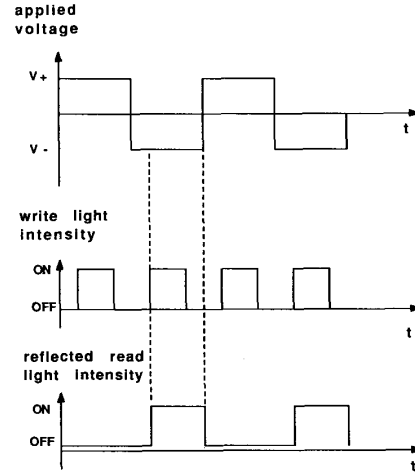


Fig. 3. Ideal response for OASLM.

write light. Adding a positive offset voltage to the square-wave voltage eliminates this spurious switching. However, this reduction of the $|V_-|$ reduces the FLC switch-on drive voltage and hence increases the response time of the device.

III. EXPERIMENTAL

The a-Si:H³ is grown at $\sim 220^\circ\text{C}$ in a PECVD multi-chamber system (plasma enhanced chemical vapor deposition system). After the deposition, a ~ 100 Å heavily boron doped a-Si:H p⁺ layer, an intrinsic layer of about 2 μm thickness is deposited, followed by a heavily phosphorus-doped n⁺ layer of ~ 100 Å thickness. The sheet resistances of the n⁺ layer, the TCO adjacent to the a-Si:H, and the TCO adjacent to the FLC are about 10^{10} , 7, and 100 Ω/square, respectively.

The collected charge as a function of frequency for the a-Si:H p-i-n photodiode layer was determined using a square-wave-response technique. A square-wave voltage of +5 to -5 V was applied at frequencies from 20 Hz to 500 kHz. The current response of the photodiode, determined from the voltage drop across a 50-Ω resistor in series with the photodiode, was measured as a function of applied voltage frequency. By integrating the current-time response curve displayed on an oscilloscope, and subtracting the dc current determined by I - V measurements (Fig. 4), the total charge collected by the a-Si:H during reverse bias at a given frequency was calculated.

An experimental arrangement to test the OASLM is shown in Fig. 5. The OASLM we tested did not have a reflecting layer. We expect that the series capacitance that a dielectric reflector would introduce would significantly alter the optimum operation conditions. An Ar laser (514 nm) write-beam incident on the a-Si:H side is absorbed by the photodiode layer. This results in an electric field across the FLC during the V_- part of the applied voltage. A polarized He-Ne laser (633 nm) read beam, incident

³Glasstech Solar, Inc., 12441W. 49 Ave., Wheat Ridge, CO 80033.

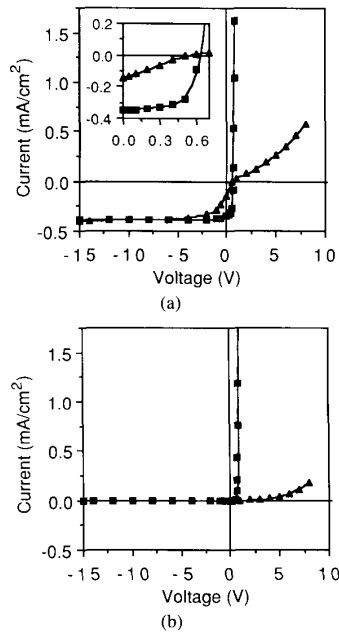


Fig. 4. Current versus voltage for the a-Si:H thin films: ■: 2- μm a-Si:H; ▲: 4- μm a-Si:H. (a) Illumination with $\sim 1 \text{ mW}/\text{cm}^2$ read light and (b) under dark conditions.

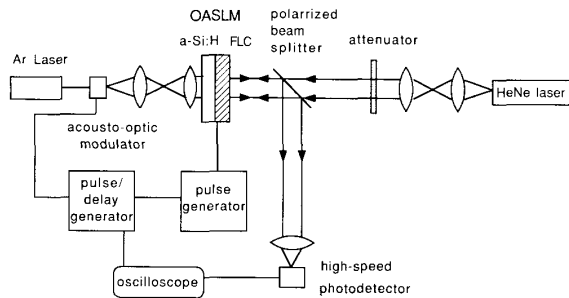


Fig. 5. Optical measurement system for the OASLM response.

upon the FLC side, is reflected at the a-Si:H/FLC interface by the change in the index of refraction. The indices for the a-Si:H and FLC are ~ 4.2 and 1.5 , respectively, resulting in the reflection coefficient of ~ 22 percent. The reflected intensity or image is measured after a crossed analyzer with a high-speed photodetector or a CCD video camera. The write (Ar) and read (He-Ne) laser beams are expanded and attenuated to produce an intensity of $\sim 6 \text{ mW}/\text{cm}^2$ and $13 \mu\text{W}/\text{cm}^2$, respectively, covering the device area of 1.5 cm^2 .

A continuous write light is used for the spatial resolution measurement. A United States Air Force resolution target is imaged onto the a-Si:H layer at a magnification of 1.2 . The reflected real image is detected by a CCD camera and displayed on a TV monitor.

IV. RESULTS AND DISCUSSIONS

The capacitance of the a-Si:H, $C_{\text{a-Si}}$, is comprised of two independent types of capacitance, depletion and geo-

metric. The former refers to the capacitance caused by the change in the amount of stored charge in the depletion layer in response to a bias-voltage change. The latter is the fixed capacitance of the a-Si:H layer which depends inversely on thickness.

Using the square-wave-response technique described in Section III, we measured the relative magnitude of the geometric and depletion layer capacitances. The capacitive units of charge per voltage were obtained by dividing the total collected charge by the magnitude of the voltage which induced the charge. At all frequencies measured, from 20 Hz to 500 kHz , the amount of collected charge was nearly the same. As the depletion layer component is expected to decrease with increasing frequency, the result indicates that the geometric capacitance completely dominates the depletion layer contribution to $C_{\text{a-Si}}$. The geometric capacitance values determined from the measurements and from the calculated value (based on the thickness and dielectric constant) are $8 \text{ nF}/\text{cm}^2$.

As mentioned in the previous section, $C_{\text{a-Si}}$ should be small compared to C_{FLC} to prevent undesired switching of the OASLM. In choosing the a-Si:H thickness, however, there is a tradeoff between high spatial resolution and fast device response. The electric field generated by point illumination extends over a small region of the FLC for a thinner a-Si:H film, which provides higher spatial resolution. On the other hand, the correspondingly larger geometric component of $C_{\text{a-Si}}$ increases the response time of the device, as explained above.

Fig. 4 shows the I - V characteristic measured for the a-Si:H deposited in the same run as that used for the device. For comparison, we also show the I - V curves for a 4- μm a-Si:H which was deposited under different conditions and used in a previous OASLM [10]. The optical response of this previous OASLM suffered from partial turn-ON in the dark. Fig. 4(a) shows I - V curves for both a-Si:H thin films with $\sim 1 \text{ mW}/\text{cm}^2$ red light illumination. In the reverse bias region, the photocurrents for both a-Si:H samples approach the same value, approximately $0.4 \text{ mA}/\text{cm}^2$. The inserted diagram indicates that the 2- μm a-Si:H has a much better fill factor than does the 4- μm sample. In Fig. 4(b), the I - V curves in the dark are shown. Both a-Si:H samples have negligible current under reverse bias. In the forward bias region, for both illuminated and dark conditions the 2- μm a-Si:H has a much larger dI/dV than the 4- μm sample. By matching a SPICE simulation to the measured I - V characteristics, we find the 2- μm a-Si:H has a $R_s = 160 \Omega - \text{cm}^2$ and $R_{\text{sh}} = 5.3 \times 10^8 \Omega - \text{cm}^2$ in the dark. R_s is much less than R_{FLC} , which is at least $1 \text{ M}\Omega - \text{cm}^2$, while R_{sh} is much larger than R_{FLC} . The 2- μm a-Si:H, which exhibits the desired I - V characteristics, provides a much improved optical performance in the OASLM over that of the 4- μm a-Si:H.

The optimal offset voltage V_{offset} is approximately $1.5 \sim 3.5 \text{ V}$ for $V_{\text{pp}} = 30 \text{ V}$. Given the values for $C_{\text{a-Si}}$ ($8 \text{ nF}/\text{cm}^2$) and C_{FLC} ($5 \text{ nF}/\text{cm}^2$), the positive V_{offset} provides a negligible negative voltage across the FLC under reverse bias in the dark, preventing the device from

partially turning ON by the capacitance dividing effect mentioned in Section II. Increasing V_{offset} , however, reduces V_- , and therefore increases the response time of the device. The device response time is limited by the response time of the FLC, which is proportional to [11]

$$\tau_{\text{FLC}} = \frac{\eta d}{PV_-}$$

where η is the viscosity of the FLC, P is its spontaneous ferroelectric polarization, and d is the thickness of the FLC.

The response of the device is shown in Fig. 6. The upper trace is the 2-kHz square-wave applied voltage. The second trace shows when the write light is ON during V_- -period. The bottom trace indicates the device is in the OFF state while there is no write light. The center trace shows the reflected read light response to the modulated write light and the applied voltage. The overall cycle time is approximately 300 μs , with a rise-delay time of 85 μs between the onset of the write light and the response, a 10–90 percent rise time of 70 μs , a fall delay time of 50 μs and a 90–10 percent fall time of 80 μs . The turn-on response time (rise delay + rise time) is 155 μs . A V_{offset} of 1.5 V is chosen so that the device is marginally in the completely OFF state in the dark.

Fig. 7 shows a photograph of a video monitor image of the OASLM being written with an Air Force resolution target. By observing the finest pattern that was resolved, we found a resolution of at least 33 lp/mm. This was observed with a 2-kHz driving voltage ($V_{\text{pp}} = 30\text{ V}$, $V_{\text{offset}} = 3\text{ V}$) and a write light intensity of 6 mW/cm². Testing the entire imaging system indicates that the spatial resolution measurement is limited by the system resolution and not that of the device.

We compare the a-Si:H/FLC OASLM to other devices in Table I. In this table, we use an optical switching energy per pixel = (intensity) \times (write time)/(2 \times resolution)². For our device, the contrast ratio falls to 3:1 at a write-light intensity of 0.4 mW/cm². Using this intensity, a write time of 155 μs , and a resolution of 33 lp/mm, we find an optical switching energy per pixel of approximately 0.15 pJ. Several a-Si:H/FLC devices are listed. The device of Takahashi *et al.* [13] is a single-pixel light valve. The OASLM of Williams *et al.* [14] incorporates a single intrinsic layer of a-Si:H on indium tin oxide (ITO) coated glass as the photosensor. We proposed [6] and demonstrated [7] that a photodiode is essential to reliably erase the device.

The design sheet resistance of the n^+ layer, $\rho = 10^{10}\ \Omega/\text{square}$, is critical in preventing lateral diffusion of the charges generated by an optical image, and thus preserving the high spatial resolution. Using a simple geometric argument, ρ may be chosen as

$$\rho \sim \frac{\tau \times (\text{Resolution})^2}{C_{\text{a-Si}} + C_{\text{FLC}}}$$

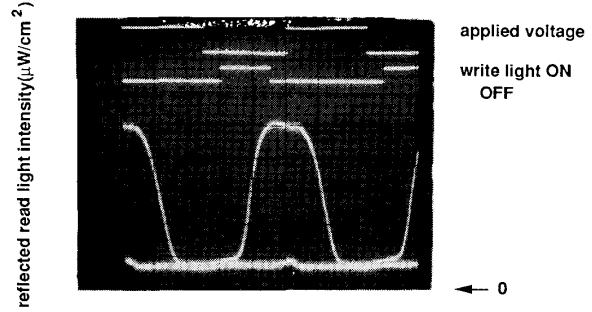


Fig. 6. OASLM responses to a 2-kHz square-wave voltage ($V_{\text{pp}} = 30\text{ V}$, $V_{\text{offset}} = 1.5\text{ V}$) and modulated write light (6 mW/cm²). Horizontal scale: 0.1 ms/div; vertical scale: 0.5 ($\mu\text{W}/\text{cm}^2$)/div.

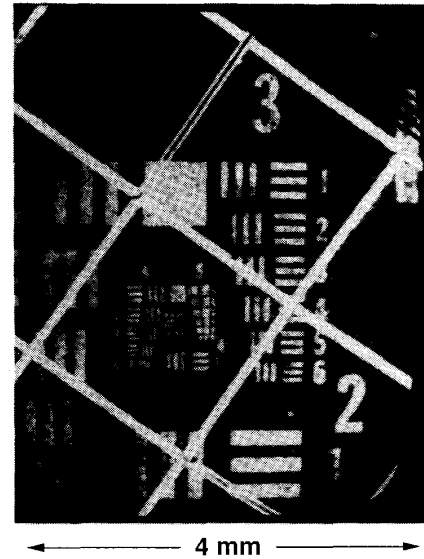


Fig. 7. Output response to USAF test target input. The grids are 2 mm \times 2 mm square patterns in the TCO coating on the glass, and show the relative scale of the USAF resolution chart. Maximum resolution is 33 lp/mm.

where τ is the response time of the device, and resolution has units of inverse length. For example, if τ is 150 μs , the resolution is 50 lp/mm (10 μm) for $\rho = 10^{10}\ \Omega/\text{square}$.

The chosen square-wave frequency must not exceed the limit of the device response, but must be high enough to maintain high spatial resolution. If the frequency is too low, the electric field corresponding to the optical image has time to spread out along the n^+ layer, and consequently reduces the resolution. Alternatively, if the frequency is too high, the device does not have enough time to turn ON and OFF completely. This decreases the contrast ratio of the output read light.

V. CONCLUSION

We have reviewed the a-Si:H photodiode/FLC OASLM optical characteristics. Analysis of the equiva-

lent circuit indicates desired parameter values of $C_{a-Si} < C_{FLC}$, $R_i < R_{FLC}$ and $R_{sh} > R_{FLC}$ for optimal operation. The various design tradeoff parameters have been discussed. Reducing the a-Si:H thickness should increase the resolution, but increases C_{a-Si} , and therefore the response time. The resistance of the n-layer was also shown to be important. Too conductive an n-layer spreads out the charge, reducing resolution. A positive offset voltage prevents the undesired turning ON of the device, but increases the response time. Using a high driving voltage frequency increases the spatial resolution, but reduces the contrast ratio of the output read light.

Further work is being done in the following areas: the development of a quantitative model that simulates the response time and modulation; measurements of uniformity and reliability; improvements in measuring systems including a high-speed detector and a high-resolution imaging system; and improvement in device switching speed, contrast, and spatial resolution.

ACKNOWLEDGMENT

The authors wish to thank D. Doroski at Displaytech, Inc., for preparing the OASLM devices; Dr. K. M. Johnson for invaluable support and discussions; J. Z. Xue and C. T. Kuo for valuable contributions; and C. Walker and P. Barbier for their comments on this work.

REFERENCES

- [1] C. S. Sexton, *Proc. SPIE Int. Soc. Opt. Eng.*, vol. 684, p. 96, 1986; also "Specifications for Model H-4160," Hughes, June 1988.
- [2] P. R. Ashley and J. H. Davis, *Appl. Opt.*, vol. 26, p. 241, 1987.
- [3] P. R. Ashley, J. H. Davis, and T. K. Oh, *Appl. Opt.*, vol. 27, p. 1797, 1988.
- [4] G. Livescu, D. A. B. Miller, J. E. Henry, A. C. Gossard, and J. H. English, *Opt. Lett.*, vol. 13, p. 297, 1988.
- [5] N. A. Clark and S. T. Lagerwall, *Appl. Phys. Lett.*, vol. 36, p. 899, 1980.
- [6] G. Moddel, K. M. Johnson, and M. A. Handschy, *Proc. SPIE Int. Soc. Opt. Eng.*, vol. 754, p. 207.
- [7] G. Moddel *et al.*, *Appl. Phys. Lett.*, vol. 55, p. 537, 1989.
- [8] N. A. Clark and S. T. Lagerwall, *Ferroelectrics*, vol. 59, p. 25, 1984.
- [9] M. A. Handschy and N. A. Clark, *Ferroelectrics*, vol. 59, p. 69, 1984.
- [10] W. Li, C. T. Kuo, G. Moddel, and K. M. Johnson, *Proc. SPIE Int. Soc. Opt. Eng.*, vol. 936, p. 48, 1988.
- [11] X. Jin-Zhi, M. A. Handschy, and N. A. Clark, *Ferroelectrics*, vol. 73, p. 305, 1987.
- [12] S. G. Latham and M. P. Owen, *GEC J. Res.*, vol. 4, p. 219, 1986; also "Specifications," 1988.
- [13] N. S. Takahashi, H. Asada, M. Miyahara, and S. Kurita, *Appl. Phys. Lett.*, vol. 51, p. 1233, 1988.
- [14] D. Williams *et al.*, *J. Phys. D.*, to be published.
- [15] T. Hara, Y. Ooi, T. Kato, and Y. Suzuki, *Proc. SPIE Int. Soc. Opt. Eng.*, vol. 613, p. 153, 1986; also "Specifications for MSLM X1699," Hamamatsu.
- [16] T. Minemoto, S. Numata, and K. Miyamoto, *Appl. Opt.*, vol. 25, p. 4046, 1986.

Wen Li (S'87-M'88) was born in Canton, China, in 1960. She received the B.S. and M.A. degrees in physics from City College of New York in 1983 and 1986, respectively. She recently received the M.S.E.E. degree from the University of Colorado, Boulder.

From 1984 to 1987, she was a Research Assistant working on solid-state physics at City College. She has worked on the optically addressed spatial light modulator since 1987. She is currently employed by Micron Technology in Boise, ID.

*

Robert A. Rice was born in Chicopee, MA, in 1961. He received the B.S. degree from SUNY at Buffalo, NY, in 1982 and the M.S. degree from Carnegie-Mellon University, Pittsburgh, PA, in 1984, both in chemical engineering. He also studied for a year at the Institute for Christian Studies in Toronto, Ont., Canada. He is currently studying towards the Ph.D. degree in electrical engineering at the University of Colorado, Boulder.

He joined Corning Glass works in Corning, NY, where he worked in Chemical Engineering Process and Development for two years. He is currently on leave, pursuing the Ph.D. degree at the University of Colorado. His research area within solid-state materials and devices includes process development and characterization of optically addressed spatial light modulators.

*

Garret Moddel (M'85) received the B.S. degree in electrical engineering from Stanford University, Stanford, CA, in 1976, and the M.S. degree in 1978 and the Ph.D. degree in 1981 in applied physics from Harvard University.

He worked in novel photovoltaic cell designs and processes in a Silicon Valley start-up company before joining the University of Colorado at Boulder in 1985. As an Associate Professor in the Department of Electrical and Computer Engineering his principal research interests are in amorphous semiconductors and thin film optoelectronic devices. He is dedicated to demonstrating the relative inadequacy of crystalline semiconductors.

*

Laura A. Pagano-Stauffer received the M.S. degree in electrical engineering from the University of Colorado in 1987.

She is currently an Optoelectronic Engineer at Displaytech, Inc., a company which develops and manufactures ferroelectric liquid crystal electrooptic devices. Most recently, she has been involved with the development of both matrix addressed and optically addressed spatial light modulators using ferroelectric liquid crystals.

*

Mark. A. Handschy received the Ph.D. degree from the University of Colorado, Boulder, in 1983.

He is Director of Research at Displaytech, Inc., where he is responsible for the development of new electrooptic products involving ferroelectric liquid crystals. Previously he was Assistant Professor of Physics at the University of Colorado, Boulder.