

# Continuing Development of an Infrared Optically Addressed Spatial Light Modulator

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## I. Introduction

The applications for spatial light modulators with sensitivity in the infrared spectrum include atmospheric compensation for imaging via phase conjugation [1], reconfigurable optical fiber interconnects and incorporation in search and track devices. The design goals for our device include: high frame rate ( $\sim 1$  kHz), sensitivity at  $1.55 \mu\text{m}$ , and a high resolution (MTF = 50% at 40 lp/mm). Meeting these design specifications has introduced many technical challenges to the project.

The foremost objective is to find a photosensor which is both infrared sensitive and compatible with the liquid crystal. An InGaAs photosensor was used in the first IR-OASLM [2,3]. Though theoretically an excellent candidate for the IR-OASLM, InGaAs presents several obstacles. A significant drawback of InGaAs is its single crystal form, which prevents easy construction of flat large area films. Second, InGaAs shows excessive dark current when used in large area ( $1 \text{ cm}^2$ ) devices such as the IR-OASLM. This is likely due to its high surface defect levels.

For many of the applications of the IR-OASLM graded phase modulation is desired. In addition, we want this to be accompanied with high frame rates, on the order of 1 kHz. Nematic liquid crystals, when constructed and driven appropriately, satisfy these requirements.

## II. Device Structure

Figure 1 shows the basic structure of the IR-OASLM.

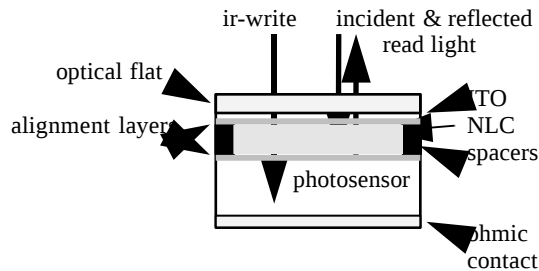


Figure 1. IR-OASLM cross-section

The photosensor has been left intentionally generic as the semiconductor could be InGaAs, as used in the past [2,3], or as we propose,  $\text{CuInSe}_2$  (CIS). An indium tin oxide (ITO) layer is deposited on an optical flat. The spacer

layer is then formed over the ITO. A dielectric stack may be included at the photosensor-liquid crystal interface.

Previous devices used glass rods [4] mixed with the adhesive to gap the liquid crystal cell. In the case of thin cells, having a thickness of approximately  $1 \mu\text{m}$ , the rods were completely eliminated, with the adhesive alone provided the gapping mechanism. This method, though convenient, required the exertion of pressure on the photosensor to attain the required gap. To reduce stress and possible micro-fracture formations within the fragile photosensor an alternative spacing technique has been developed.

The heart of this alternate gapping method is negative photoresist. Standard photolithography techniques are used to create the spacer layer. Negative photoresist is spun-on to the desired thickness. A mask is then used to create a structure as shown in the lower right of figure 2.

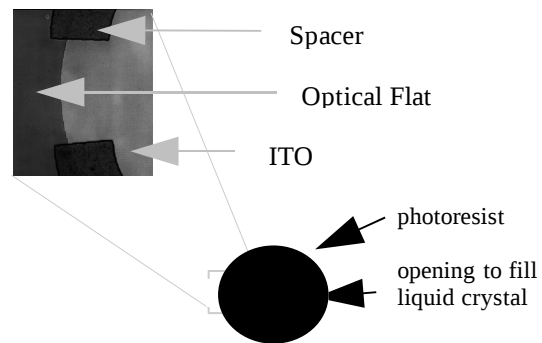


Figure 2. Top profile of the spacer layer. The lower right figure depicts the entire spacer structure. A small portion is expanded in an actual photograph in the upper left.

The negative photoresist is exposed to ultra-violet light and developed to create the spacer structure. The viscosity of the photoresist, 747 [5], is varied depending on the desired spacer thickness. Negative resist was chosen for its resistance to cleaning chemicals (acetone, methanol etc.) and the ability to control and attain the desired thickness. When necessary, multiple layers of photoresist are used to create thicker spacers. Spacer layers up to  $4 \mu\text{m}$  have been easily and repeatedly produced.

## III. Photosensor Material

Initial IR-OASLMs incorporated an InGaAs photosensor [2,3], which should be acceptable for use in the IR-OASLM. InGaAs has a very low dark current when tested in small mesa structures ( $< 10^{-6}$  A/cm<sup>2</sup>). Additionally the bandgap of InGaAs offers optical sensitivity in the desired 1.55  $\mu$ m regime. Unfortunately, InGaAs OASLMs have thus far produced low contrast ratios (2:1 and lower). This is due to the dark switching of the liquid crystal layer [6]. As predicted by the MIS model [7], if the dark current is too high in the photosensor an excessive amount of charge will be created at the photosensor-liquid crystal interface. This charge will then produce an electric field across the liquid crystal which causes the liquid crystal molecules to switch in the absence of a write light. This high leakage current in the InGaAs may be due to the large number of defects on its surface, as shown in figure 3. Defects with heights greater than the 1  $\mu$ m gap of the cell have been found on the InGaAs samples.

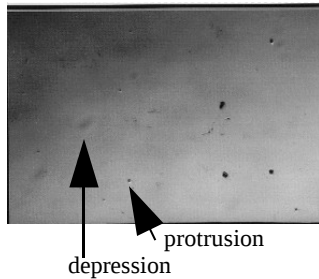


Figure 3 - An optical microscope photograph of the InGaAs surface (5X). Note the extensive protrusions and depressions.

A further concern with InGaAs is the bowing which occurs due to the lattice mismatch of the InP substrate with the InGaAs [3]. This results in an uneven gapping of the liquid crystal layer.

CIS is a popular semiconductor in solar energy applications, because of its high conversion efficiency [8]. Extensive research has been undertaken on CIS to optimize its operation in the fourth quadrant of the I(V) curve, as required for solar cell operation. To obtain adequate I(V) characteristics for OASLMs we must optimize the third quadrant to ensure large reverse breakdown voltages and low dark current. This means that direct use of the available solar engineered CIS is not acceptable for the IR-OASLM.

Because of the fourth quadrant optimization and inherently high dark current, CIS has not been a serious candidate for OASLMs in the past. However, by incorporating barriers, either Schottky or heterojunctions, the dark current can be reduced to acceptable levels. Devices using (p) CIS and (n) a-Si:H show dark currents as low as  $9.4 \times 10^{-8}$  A/mm<sup>2</sup> [9]. An I(V) curve of our first CIS/a-Si:H heterojunction is shown in figure 4. Furthermore, the low carrier mobility in the a-Si:H enhances the spatial resolution of the OASLM [10].

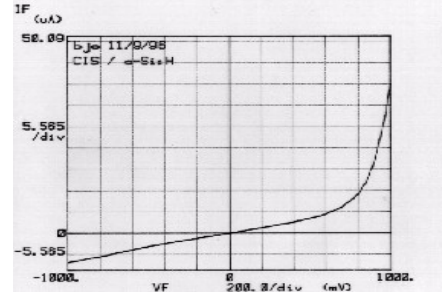


Figure 4. I(V) characteristics of a (p) CIS / (n) a-Si:H heterojunction. The thickness of the a-Si:H layer is 400 nm with a  $3 \times 10^3$  phosphine-to-silane ratio. The CIS : 2.5  $\mu$ m; atomic % : Cu-23.08 In-27.75 Se-49.68; Area=8 mm<sup>2</sup>

The ability to deposit CIS in thin film form give it a significant advantage over crystalline InGaAs. Thin film photosensors allow the construction of inexpensive, flat, large-area devices. The flatness of CIS can be controlled by depositing onto an Mo coated optical flat. Mo provides an optimal ohmic contact to CIS while the optical flat assures photosensor flatness.

The a-Si:H CIS heterojunction offers not only low dark current, but also excellent resolution. The origin of this improved resolution is clear when one looks back at the basic OASLM operation. The OASLM modulates the read beam due to the birefringence of the liquid crystal, which is controlled by creating a spatially varying electric field. This electric field is created when electron-hole pairs are generated within the photosensor due to the incident write light. The charge carriers are swept towards (or away from) the liquid crystal photosensor interface by the applied reverse bias. With a low lateral resistance at this interface, the charge carriers will not spread, and therefore the write image will be accurately reproduced. Should the lateral resistance be too low, these charge carriers will spread, distorting the write image and decreasing the resolution [10]. The mobility of carriers in a-Si:H is very low ( $\mu_{\text{holes}} = 0.01$  cm<sup>2</sup> / V•s &  $\mu_{\text{electrons}} = 1$  cm<sup>2</sup> / V•s ), which prevents charge spreading and thus provides high resolution. This is evident in the a-Si:H OASLMs our group has previously produced [11].

The bandgap of crystalline CIS is 1.01 eV. This means the absorption will be limited to wavelengths below 1.3  $\mu$ m. This is an issue that must be dealt with if CIS is to be used in the IR-OASLM. However, narrowing of the bandgap is possible by doping the CIS with Fe [12]. This may enable CIS to work farther into the infrared.

#### IV. Liquid Crystal Considerations

Ferroelectric liquid crystals (FLCs) have the advantage of fast switching speeds due to the built in dipole. With a dipole, we can drive the molecules to either orientation state [13]. The disadvantage of FLCs is

evident when one seeks to make the OASLM produce a graded phase modulation.

Nematic liquid crystal, due to the achievable graded phase modulation, appears to be more appropriate in the IR-OASLMs. The disadvantage of nematic liquid crystal is its response time. The molecules respond only to the rms value of the applied voltage, which means the response of the nematic liquid crystal molecules is sign independent and an applied voltage can only drive the NLC to one of its given states. The return to the original state is accomplished by removing the voltage and allowing the molecules to naturally relax to their original orientation [14].

Due to the slow relaxation of the nematic liquid crystals we must employ various techniques to increase the maximum frame rate of the device. We begin by incorporating parallel alignment layers [15]. This creates a unidirectional flow when the molecules are relaxing to their original state. Note in figure 5, when an electric field is applied across the cell, the molecules above and below the central layer rotate in the same manner, resulting in the unidirectional flow on the central layers.

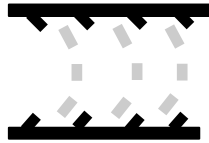


Figure 5. Parallel alignment - The dark structure depicts the cell boundaries and alignment layer, while the gray depicts the molecular orientation.

In addition, we incorporate the transient nematic effect [16]. The transient nematic effect requires that the cell is operated in its last transmission cycle. A plot of the optical transmission versus the rms of the applied voltage is first created with the transmission maximum at zero volts rms. The transmission then drops to zero at a critical voltage and oscillates before decaying back to zero transmission at higher voltages. By operating in the last transmission cycle only the molecules near the interfaces of the cell are responsible for the optical modulation, with the molecules at the central layers remaining virtually unaltered. With this technique we have obtained 1 ms relaxation times. By further optimization of alignment layers and cell thickness we expect to obtain shorter response times. Wu and Wu have demonstrated the transient nematic effect with relaxation times of 100  $\mu$ s [16].

## V. Conclusions

By combining several techniques together, we have arrived at a method which will make the IR-OASLM more practical. First, we will use thin film photosensors which offer low dark current and high resolution. Second nematic liquid crystal will be used since they offer graded-phase response with sufficiently fast switching rates. Finally, the alternative gapping technique will be used to allow accurate repeatable

gapping. The preliminary results are promising that the speed, resolution and sensitivity requirements can be met.

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