Design of an optically addressed spatial light modulator sensitive to 1.55-μm write light

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I Introduction

Most optically addressed spatial light modulators (OASLMs) utilize photosensors of hydrogenated amorphous silicon (a-Si:H), Si, GaAs, CdS, CdSe or other photosensors which are sensitive from visible to near IR wavelengths (< 1.1 μm). Some applications such as correction of atmospheric turbulence in the eye-safe region of the spectrum for free-space optical communication demand OASLMs that have high sensitivity at 1.55 μm, high frame rate (> 1 kHz), and high resolution (MTF = 50% at 40 lp/mm). Ferroelectric liquid crystal (FLC) has very fast response and FLC OASLMs can be operated at frame rates of a few kHz[1]. An IR-OASLM with an $In_{0.53}Ga_{0.47}As$-InP photosensor and an FLC light modulating layer is being developed in our laboratories. The design, preliminary experimental results, and practical issues for such an IR-OASLM will be presented and discussed.

II Photosensor material

We have investigated various types of IR photosensors which include thermal, internal photoemission, organic, and photon detectors. Among them, intrinsic semiconductor photosensors offer good performance in terms of responsivity and dark current. The photosensor in the IR-OASLM should be sensitive at 1.55 μm, but also have as large an energy bandgap as possible to avoid the excessive thermal current and large dark conductivity that are associated with narrow-bandgap semiconductors.

OASLMs that incorporate photosensors of crystalline Si or GaAs are biased alternately in erase and write periods[2-4]. In the write period, the dark current must be sufficiently low that the device does not switch on in the absence of illumination. A reverse-biased *pin* photodiode is similar to the OASLM in the write period in its dark current generation mechanism. Therefore a semiconductor that is used to make IR *pin* photodiodes with low dark current could also be used in the IR-OASLM. InGaAs-InP *pin* photodiodes have dark currents from 5×10^{-5} to as low as 4×10^{-8} A/cm^2[5-7]. InGaAs films also have a large absorption coefficient at 1.55 μm wavelength (8000 cm^{-1}). Therefore we choose InGaAs-InP as the photosensor for the IR-OASLM.

III IR-OASLM structure

One of the possible IR-OASLM structures that is used in Si and GaAs OASLMs is illustrated in Fig. 1(a). The intrinsic InGaAs is slightly n-type. The n^+-InP wafer serves as the ohmic contact to the intrinsic layer.

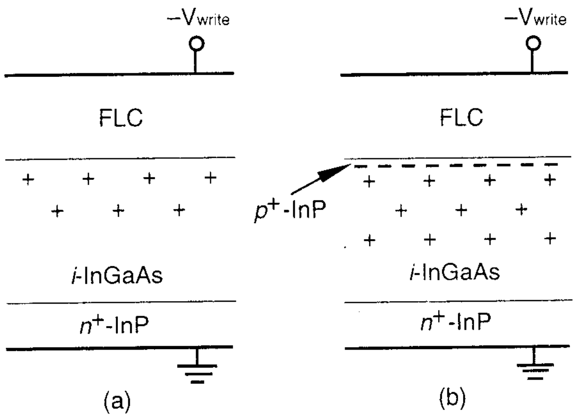

Fig. 1 Two possible structures of the IR-OASLM: (a) without, and (b) with a p^+-InP layer.

When a positive erase-voltage V_{erase} is applied to the device, an electron accumulation layer forms near the FLC–InGaAs interface and the voltage across the FLC is equal to V_{erase}. The FLC layer is considered to be in its off-state. When a negative write-voltage $-V_{write}$ is applied, the electrons are swept out and a depletion layer forms in the InGaAs layer. The initial voltage in the FLC during the write period should be close to zero volts so that the FLC remains in its off-state in the absence of write light. Fig. 2 shows this initial voltage in a 1-μm FLC and the corresponding depletion width for V_{write} = 5 V (assuming a thick InGaAs layer). It is clear that to keep the FLC in its off-state in the absence of write light the residual doping in InGaAs must be very small (< 10^{13} cm^{-3} for less than 1 V in FLC) and the InGaAs layer must be very thick (> 20 μm). Unfortunately, InGaAs can be grown only on InP wafers in thin-film form with residual doping ≥ 5×10^{14} cm^{-3}. Most of the write voltage is dropped in the FLC layer if the IR-OASLM incorporates only such an intrinsic InGaAs. In this case the FLC would switch to its on-state even in the absence of write light.

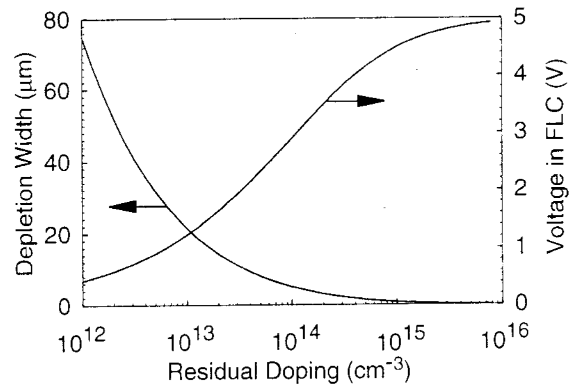

Fig. 2 Calculated depletion width in InGaAs and the initial voltage in the FLC versus residual doping in InGaAs. V_{write} = 5 V is assumed.

The large initial voltage in the FLC can be reduced by depositing a thin layer of p^+-InP on top of InGaAs, as shown in Fig. 1(b). InP is the preferred material over InGaAs for the reason discussed in Section V. When the voltage V_{erase} is applied to the device, electrons flow toward the p^+-InP layer and holes in p^+-InP are swept out or recombine with electrons. As a result a sheet of ionized acceptors are left in the p^+-InP layer with charge density of $-\varepsilon_{lc}V_{erase}/d_{lc}$, where ε_{lc} and d_{lc} are the dielectric constant and thickness of the FLC layer, respectively. When the voltage V_{write} is applied to the device, electrons in the intrinsic layer are swept out as in the configuration of Fig. 1(a). However, the acceptors *remain* ionized in the p^+-InP layer, which lowers the potential at the interface and *reduces* the voltage in the FLC layer. Thus the initial voltage across the FLC during the write period can be adjusted by changing V_{erase} in the erase period. Fig. 3 shows the value of V_{erase}

that is needed to keep the initial voltage in a 1-μm FLC layer zero volts for a 3-μm InGaAs layer and V_{write} = 5 V. The corresponding depletion width in the InGaAs layer is also shown. With low residual doping, the InGaAs layer is fully depleted and V_{erase} is slightly larger than V_{write}. When the doping level increases, however, the depletion width decreases and the corresponding required V_{erase} grows and a very asymmetric driving waveform is needed.

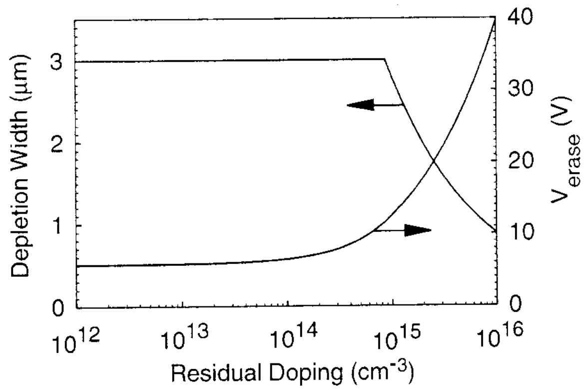

Fig. 3 Calculated depletion width in InGaAs and the required V_{erase} to keep the voltage in the FLC zero volts in the write period versus residual doping in InGaAs. V_{write} = 5 V is assumed.

A photosensor that consists of a thin p^+-InP (< 100 nm) layer on top of a few micron intrinsic InGaAs layer is required in the proposed IR-OASLM. An InGaAs layer with low residual doping is desirable to reduce the asymmetry in the driving waveform.

IV IR-OASLM characterization

An IR-OASLM with the structure of Fig. 1(b) was assembled and tested. The SCE13 FLC is 1 μm thick, the 0.1 μm p^+-InP layer has a doping concentration of 2×10^{17} cm^{-3}, and the 1.9 μm intrinsic InGaAs ~10^{16} cm^{-3}[8]. The write light (1.55 μm) is incident from the FLC side. Fig. 4 shows the transient response with a read light of 633 nm. The IR-OASLM can be operated at frame rates from 0.3 to 5 kHz. Its sensitivity at 1.55 μm is ~1 mW/cm^2 and the best contrast ratio is 2:1.

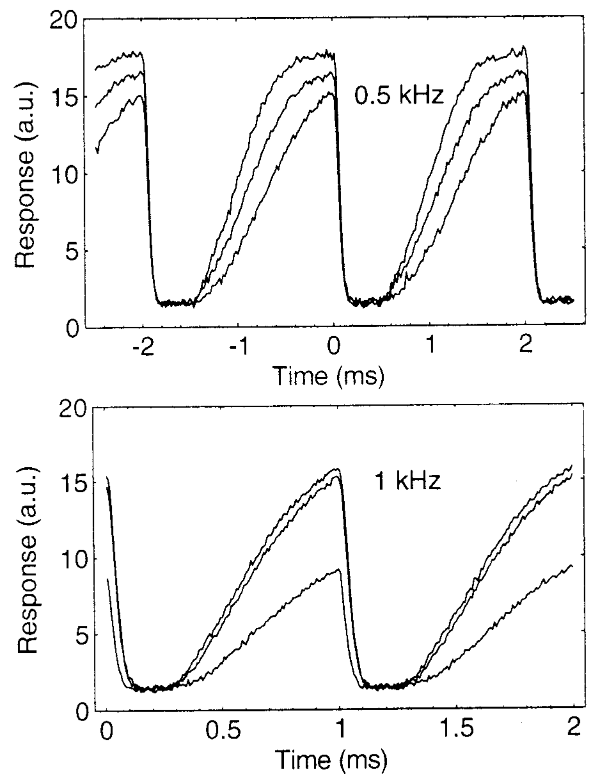

Fig. 4 Intensities of reflected read light from the IR-OASLM at frame rates of 0.5 and 1 kHz for write-light intensities of 0 (lowest curves), 1 (middle curves), and 2.5 mW/cm^2 (upper curves).

The partial switch-on of the FLC layer in the absence of write light is due to the large dark current from the InGaAs-InP photosensor. The frame rate of the IR-OASLM is limited by the switching speed of the FLC layer. In this test device the spatial resolution is very poor because of substantial charge spreading at the FLC–photosensor interface. We have also found that the FLC layer is not uniform. This is caused by the bow or warp in the photosensor, which is due to the minor lattice-mismatch and thermal expansion difference between InGaAs and InP.

V Practical issues

An IR-OASLM that incorporates an InGaAs-InP photosensor has been demonstrated. The resolution, uniformity, and contrast ratio have to be investigated and improved to make practical devices.

From our recently developed resolution model[9] we have found that the carrier mobility and trapping time at the FLC–photosensor interface have to be very small for high resolution (diffusion length must be less than 3 μm for resolution of 10 lp/mm). One solution is to deposit a thin layer of a-Si:H on top of the p^+-InP. The photogenerated minority carriers in InGaAs are holes. The hole mobility in a-Si:H is very small (~0.01 cm^2/V s) and the charge spreading can be significantly reduced. The key to the success of this technique is to avoid having excessive dark current generated at the a-Si:H–InP heterojunction. Because the energy bandgap of InP (1.35 eV) is much larger than that of InGaAs (0.75 eV), it is expected that an a-Si:H–InP heterojunction[10] would result in much smaller dark current than an a-Si:H–InGaAs heterojunction.

A uniform gap between the optical flat and the photosensor is necessary for an IR-OASLM with large active area. The flatness of the photosensor could be improved by thinning and polishing the backside of InP wafer before bonding. An epitaxial liftoff technique offers another possibility[11].

The contrast ratio of the output from the IR-OASLM can be improved by reducing the dark current from the photosensor. This may be accomplished by using high quality InGaAs-InP photosensors. The contrast ratio can also be improved by increasing the frame rate so that the amount of charge generated by the dark current in each write period is reduced.

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