PHOTOCONDUCTIVE OPS-POLYIMIDES AND THEIR APPLICATIONS FOR OPTO-ELECTRONIC DEVICES (II) : SPATIAL LIGHT MODULATORS

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A novel spatial light modulator (SLM) has been proposed and fabricated. The SLM consists of OPS-Polyimides (OPS-PI) spin coated thin films as photoconductive layers and smectic C* ferroelectric liquid crystals (FLCs) as modulating layers. The SLM shows a nonlinear optical response against the optical inputs, which can be used for parallel processings in optics. The threshold value of an input light intensity for switching can be controlled by changing the applied voltage, which is very useful in implementing the optical neural networks.

1. Introduction

Recent years, a variety of spatial light modulators (SLMs) have been studied and developed for the real time optical information processings and the image projection. In these fields, high sensitivity, high resolution, fast response and good con-

trast ratio of output image are needed. SLMs using ferroelectric liquid crystal (FLC) and photoconductors are shown as promising devices because of high resolution capability(>100 lp/mm) and fast switching speed ($< 100 \mu$ sec) between two stable states. As a photoconductor, CdS¹⁾, c-Si²⁾, c-GaAs³⁾ or a-Si⁴⁻⁸⁾ has been used. Mylnikov reported the SLM using the organic photoconductor.⁹⁾ In this work, we propose a SLM using FLC and OPS-PI as a photoconductor.^{10,11)} And opto-electronic response properties of the fabricated device are also shown. In this device, the OPS-PI layer can be acted as an alignment layer of FLCs. A lot of works of alignment layer materials for FLCs suggested that alignment layers having a high conductivity give good bistability and memory of the FLC.^{12,13)} OPS-PI have a good conductivity for the purpose of aligning FLCs.

2. Device fabrication

SLMs using OPS-PI spin coated thin films as photoconductive layers and smectic C* FLCs as modulating layers were fabricated. Figure 1 shows the schematic structures of SLMs operated in a reflection-mode (a) or in a transmission-mode (b). In both modes a write beam is irradiated on the side with OPS-PI layer of the

Fig. 1 Cross sections of SLM showing OPS-PI photoconductive layer and FLC light modulating layer (a) in a reflection-mode and (b) in a transmission-mode

device. The beam is absorbed in that layer and creates a spatially varying electric field, which modifies the state of FLC. In reflection-mode (a), the read beam irradiated on the side with the modulating layer transmits the layer and reflects at the mirrors, then goes back through the modulating layer. In transmission-mode, the read light with a longer wavelength than that absorbed in the OPS-PI layer is irradiated on the side with that layer and passes through the modulating layer.

The device was fabricated as follows: the polyamic acid prepolymer of OPS-PI dissolved in N,N'-dimethylacetamide (DMAc) was cast on an indium-tin-oxide (ITO) transparent conductive glass with the sizes $35 \times 35 \times 1.1 \text{ mm}^3$ and then was imidized and crystallized by annealing at 300°C for about 2 hours. The thickness of the OPS-PI film was $2 \text{ }\mu\text{m}$. Well crystallized BPDA-Ph^{310,11)} with the size of crystallite of about $130 \text{ }\text{\AA}$ had a high sensitivity of $\eta \mu \tau = 10^{-8} \text{ cm}^2/\text{V}$ in the visible light region (400-570nm), where η is generation efficiency, μ is carrier mobility and τ is carrier life time. In the reflection-mode cell, the reflective 6×6 mirrors of Al electrodes ($2.5 \times 2.5 \text{ mm}^2$) were formed by the evaporation on the surface of the OPS-PI film. A rubbed OPS-PI thin film of $200 \text{ }\text{\AA}$ thickness on both the mirrors and an another optical flat glass coated with ITO aligns the FLC. The tilt angle of the FLC used (ZLI-3654, Merck) is close to 22.5° , resulting in a rotation of the optical axis through approximately 45° under an applied electric field. Hence the FLC acts on the function as an electrically controlled wave plate. Ideally the thickness of the FLC layer is chosen such that $2d\Delta n = \lambda/2$, where Δn is the FLC birefringence (0.13 of ZLI-3654) and λ is the read-light wavelength. Glass rods of about $1 \text{ }\mu\text{m}$ diameter for (a) in Fig. 1 and $2 \text{ }\mu\text{m}$ diameter for (b) in Fig. 1 were sprayed on one side of the substrate so as to ensure forming the surface stabilized FLC (SSFLC).¹⁴⁾ The two glass plates were then set parallel and face-to-face, separated by the spacers to form a cavity. A small amount of FLC was placed on the open edge of the cavity and set on a temperature controlled stage in a vacuum chamber. When the stage was heated to the temperature at which the FLC was in its isotropic phase (over 86°C in ZLI-3654),

the FLC fill the cavity by capillary action. The device was slowly cooled to room temperature at which the FLC was in its smectic C* phase (between -30°C and 62°C in ZLI-3654).

3. Opto-electronic properties

3.1. Operational Principle

Figure 2 shows an equivalent circuit for the SLM device. In the interface of ITO and OPS-PI, Schottky type contact is made. Figure 3 (a) shows the energy band diagram of ITO/OPS-PI/Al, which was determined by the data on an optical energy gap, E_g , ionization potential, I.P., and work function.¹⁵⁾ The ITO film used was an n-type degenerate semiconductor and its E_g is around 3.7 eV.¹⁶⁾

To operate the device, the pulse voltage is applied between the two ITO layers. As shown in Fig. 3 (b), electrons injected from the ITO electrode are flowed through the bulk film layer in the case of ITO-/OPS-PI/Al⁺ and all the voltage drops across the FLC layer. So the negative pulse voltage (V_{in}^-) is applied to turn the state of the FLC to what we defined ON state. And the state of the FLC is independent of any write beam during this period. The read-out period with the zero biased voltage is set, when the FLC remains that ON state because of FLCs bistable characteristic.¹⁴⁾ When the positive pulse voltage (V_{in}^+) is applied in the absence illumination, there exists an energy barrier for holes between ITO and OPS-PI to inject. So the V_{in}^+ is divided to V_F and V_{PI} according to the resistivities of OPS-PI and FLC. The value of V_F is less than the threshold value necessary to switch the FLC and so the FLC remains OFF state. As shown in Fig. 3 (c), if a write beam illuminates OPS-PI layer, the electron-hole pairs are generated and holes are transported across the layer by the positive electric field in the ITO⁺/OPS-PI/Al⁻. And the collected positive charges at the Al electrode make almost the all voltage (V_{in}) drop across the FLC layer to switch the FLC OFF state. Thus, an erase operation takes place during the negative pulse voltage, a write operation occurs during the positive pulse voltage and the state of FLC is read-out during the interval time without the biased voltage.

Fig. 2 Equivalent circuit for the SLM in which the left side represents the OPS-PI layer and the right side the FLC layer

Fig. 3 (a)
Energy diagram of
ITO-OPS-Al

Fig. 3 (b)
Electron injection from
ITO electrode in the
negatively biased

Fig. 3 (c)
Transporting holes
generated by irradiation
from ITO side in the
positively biased

3.2. Optical switching properties

Figure 4 shows typical oscilloscope trace of the electrical response of the device in the reflection-mode. Operations were carried out with positive and negative pulse voltage (V_{in}) of 10 V in 1 msec pulse width and the read-out interval periods of 50 msec. In the absence of the illumination, the FLC remains ON state all the time as shown in Fig. 4 (a). In illuminating the device with the green light ($\lambda = 550\text{nm}$) of 7 mW/cm^2 intensity, the FLC turn to both states (ON and OFF) by applying the each pulse voltage as shown in Fig. 4 (b). It makes sure of the bi-stability of the FLC.

Fig. 4 Oscilloscope traces of optical output in applying pulse voltage (a) without or (b) with optical input

Figure 5 shows a change of transmission defined as the read-out intensity difference between OFF state and ON state as a function of the incident light intensity. The FLC could be switched when the light was irradiated with the intensity of larger than about 3 mW/cm^2 . The threshold value can be controlled by changing the value of an applied voltage, V_{in} , as shown in Fig. 6. With the same time intervals, the threshold value was

Fig. 5 Transmission as a function of incident light energy

increased with the decrease of V_{in} between 6.0 V and 9.4 V. The FLC has a threshold value, $V_F(th)$, to turn the state. V_{in} is divided to V_{PI} and V_F as the equation (1). (See Fig. 2)

$$(1) V_F = V_{in} \cdot Z_F / (Z_F + Z_{PI}(bright))$$

$$Z_F = R_F + 1/j\omega C_F : Z_{PI} = R_{PI}(bright) + 1/j\omega C_{PI}$$

where R_F, R_{PI} are resistivity of FLC and OPS-PI respectively. C_F and C_{PI} are capacitances of FLC and OPS-PI. $R_{PI}(bright)$ can be reduced with increase of the illuminating intensity. When the condition of $V_F > V_F(th)$ is satisfied, the FLC can be switched. So the decrease of V_{in} requires the decrease of $R_{PI}(bright)$ so as to satisfy that condition. It means that more intensity of an incident light is needed.

The maximum value of the V_{in} for the switching is determined by the equation (2). And also the minimum value is by the equation (3). Each experimentally determined value was around 9.4 V and 4.8 V, respectively.

$$(2) V_{in}(max) < V_F(th) \cdot Z_F / (Z_F + Z_{PI}(dark))$$

$$(3) V_{in}(min) > V_F(th)$$

Controlable threshold value of the optical switching device is very useful for the optical processing system or the optical computing. The optical neural networks will be able to be implemented with neurons having variable threshold values.^{7,8)}

Fig. 6 Optical responses against varied applied voltage

Fig. 7 Optical response of SLM in a transmission-mode

The device of the transmission-mode as shown in Fig. 1 (b) was fabricated and examined of its opto-electronic characteristic. In this device structure, the OPS-PI layer played roles of both the photosensor and alignment at the same time. In applying the same pulse voltage as the device in the reflection-mode mentioned above, the white light beam was incident. The light beam absorbed in BPDA-Ph3 generates currents to turn the FLC. And the light having wavelength longer than about 650 nm which coincides with an optical absorption edge of BPDA-Ph3, was used for a read-out beam. Figure 7 shows a read-out transmission intensity defined before as a function of the incident light intensity. When the incident light intensity was larger than the threshold value, the read-out light was in proportion to that intensity because the FLCs shutter was full opened. So the input of blue or green light was converged to the output of red light in this mode.

Switching speed of FLCs is less than several hundreds of micro seconds in electrical performing.¹⁴⁾ And we reported that of optical performing in SLM using a-Si photoconductors was about 30 μ sec.⁹⁾ The switching speed of this work was evaluated to be longer than 10 msec. It was because that the $\eta \mu \tau$ of a-Si is 10^{-6} cm²/V, which is two orders of magnitude larger than that of BPDA-Ph3. High speed performance will be obtained by using OPS-PI films having high mobility, that is, high crystallinity.^{10,11)}

To realize good bistability in the SSFLC mode, alignment layers are needed which are capable of neutralizing accumulated surface charges brought about by electrical polarization. Some ways are offered; using polyimide Langmuir-Blodgett ultrathin films¹⁷⁾ or doping polyimide cast film with a charge-transfer complex.⁹⁾ Or electrical conductive polypyrrole film was reported to realize the good bistability of SSFLC.¹⁸⁾ OPS-PI films are conductive because of thier high transporting ability of holes. And we demonstrated OPS-PIs alignment ability by fabricating the opto-electronic device, the optical neuron device (OND).^{7,8)}

4. Conclusions

Spatial light modulators using OPS-PI thin films as

photoconductive layers and FLCs as modulating layers were fabricated and demonstrated the nonlinear optical response against the optical inputs. The threshold value of light intensity to switch the state of FLC could be controlled over the range of two orders of magnitude, 0.1 to 10 mW/cm², by changing the applied voltage. In the transmission-mode configuration, input data of blue or green light could be converged to output of red light because of an optical property of OPS-PI.

5. References

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