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LIQUID CRYSTAL IMAGE CONVERTER BASED ON THE CHOLESTERIC-NEMATIC PHASE TRANSITION WITH STORAGE

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Résumé. — Un convertisseur d'images (CI) basé sur la combinaison de la structure du type semi-conducteur-diélectrique et cristal liquide est examiné. Les caractéristiques particulières de ce convertisseur d'images sont l'utilisation des semi-conducteurs aux zones étroites et le court temps d'exposition non limité par l'inertie du cristal liquide. L'utilisation de l'effet électro-optique, celui de la transition de la phase cholestérique-nématique, a quelques avantages : le haut contraste, les basses tensions gérées, le seuil précis, la possibilité de traduire l'image en positif ou en négatif.

Abstract. — The image converter (IC) based on the combination of semiconductor-dielectric (SD) structure and liquid crystal (LC) had been described in [1]. The presence of SD structure in photo-sensitive part of IC, implies some original features : a) The possibility of using narrow band semiconductor (Si) as a photosensitive material in pair with LC which enlarges the spectral range in infrared part of spectrum. b) Considerable decrease of image exposition time ($\sim 10^{-9} \div 10^{-7}$ s), which is not limited by inertia of LC in this type of IC.

The following electrooptic effects in LC were used in [1] : dynamic scattering, dynamic scattering with storage, S-effect. IC based on LC with cholesteric-nematic (CN) transition with storage is investigated here. The storage effect observed in thin cells is produced by the texture changes [2-6]. When the layer thickness being of the same order as spiral pitch P the surface pinning energy is significant. As a result we have deformed spiral superstructure, called in [4] the *strains* structure (ST). The period of this superstructure can exceed P essentially. This effect was considered for normal surface orientation of LC molecules in [2, 4, 6] and in [3, 5] it was shown that ST can be obtained for the parallel orientation of LC molecules and untreated cells. In [3, 5] it was demonstrated that ST existence depends not only on the d/P correlation, but on the influence of electric field. That is in certain cases if the initial structure is not deformed ST is formed after the nematic state. This effect is observed in the regime of electric field rapid switching off, the field voltage being more than the voltage of the CN transition (U_{CN}). When the electric field less than U_{CN} is applied, the confocal texture (CT) is formed. As the ST is formed also in the cells with the parallel orientation of molecules, we can observe the following texture changes : the planar texture $PT \rightarrow CT \rightarrow ST$. ST is more transparent than CT and darker than PT. ST as well as CT is kept a long time as a result we can get both the negative and positive image in the same cell, when the applied voltage increases. These are the advan-

tages of CN transition effect in comparison with the effect of dynamic scattering with storage : high contrast, low drive voltage, sharp threshold, possibility of transformation of input image into a positive or negative one.

1. Experiment. — The configuration of IC is illustrated on figure 1. The structure mentioned is just a puck like silicon monocrystal with $2 \div 3$ cm diameter, 2×10^{-2} cm thickness and with transparent 2×10^{-5} cm thick dielectric (SiO_2) on both sides. The LC thickness $18 \mu\text{m}$ is sandwiched between the transparent indium oxide electrode on the glass plate and dielectric-semiconductor structure. The input face of IC is covered with transparent electrodes. The nematic-cholesteric room temperature mixture with $\Delta\epsilon > 0$ and $P = 3 \mu\text{m}$ is used.

FIG. 1. — Configuration of IC. 1 : electrodes, 2 : dielectric layers, 3 : semiconductor, 4 : LC, 5 : pulse voltage, 6 : laser, 7 : collimator, I : input image, II : read-out image.

The input image is formed by means of the GaAs diodes. The reading of an image is realized either through the He-Ne laser, or *white* light. For the last case the suitable filters which prevent photoconductor from the read-out light beam are used. Read-out of image can be realized both in the reflective and the scattering light. Either the pulse voltage with the duration $\sim 10 \div 10^3 \mu\text{s}$ and frequency

$$\sim 50 \div 5 \times 10^4 \text{ Hz}$$

or AC field with the frequency not more than 100 kHz were applied to IC electrodes. In the combined system under the light LC goes into the nematic state, when the general voltage level is 71 V. In this case the positive image was formed in the mirror reflected light beam and the negative image was formed in the scattering light (Fig. 2).

a)

b)

FIG. 2. — A photograph of converted image in a nematic state (a) and strains texture state (b).

The storage effect is observed after the rapid voltage switch off some seconds later the positive image with diminished contrast 40 : 1, was formed in the mirror reflected light. Erasing and recording were realized with the help of voltage regulation. In this case there was a possibility to record down the image when the voltage applied was less than U_{CN} and the mentioned initial orientation had to be planar. In 18 V electric field we have inverse picture :

the positive image is formed in the scattered light and this image is kept after the voltage switch off (Fig. 3). The erasure in this position is carried out either with the help of mechanical displacement of the substrate or through heating the system up to isotropic state and further slow cooling.

FIG. 3. — A photograph of converted image in a confocal texture state.

If the voltage more than U_{CN} is applied to the cell mentioned in the figure 3, the part where image is formed goes into nematic structure and the rest part into the confocal one. The resulting picture is illustrated in figure 2.

The overall performance characteristics of the IC are : the rise time 0.2 ms ($d = 18 \mu\text{m}$, $U = 150 \text{ V}$), maximum contrast ratio : 100 : 1, sensitivity $\sim 10^{-8} \text{ J/cm}^2$ ($\lambda \approx 0.9 \mu\text{m}$, $\tau = 1 \text{ ms}$) and resolution 20 lines/mm.

2. Discussion. — Now we'll consider the layer matching conditions and the dynamic of processes. Let the voltage pulse with the amplitude U_0 be applied to the IC electrodes. Free carriers are drifted the semiconductor volume and accumulated on the layers interface. If the initial carrier concentration is not sufficient for screening of external voltage, than in the semiconductor a depleted layer arises :

$$L_d = \left(\frac{\epsilon_s U_0}{4 \pi q n_0} \right)^{1/2}. \quad (1)$$

For $U_0 \approx 10^2 \text{ V}$, $n_0 \sim 10^{12} \text{ cm}^{-3}$, $\epsilon_s \sim 10$, $L_d \approx 10^{-1} \text{ cm}$. Hence, when thickness of the layer of the semiconductor is $L_s \approx 2 \times 10^{-2} \text{ cm}$, $L_d \gg L_s$. The depletion is spread on the whole bulk of the semiconductor. In this case the whole voltage is distributed on the semiconductor layer and therefore there exists a strong field $E_s = U_s/L_s$. In such a case the diffusion current and the space charge field can be neglected and the equation of continuity can be written as follows [7, 8].

$$\frac{dn}{dt} = G_0 - \frac{n}{t_{dr}} \quad (2)$$

where $G_0 = n_0/\tau_0$ is the current termogeneration speed, τ_0 , life time, $t_{dr} = L_S/\mu E_S$, drift time. For $E_S > E_{sat}$ (E_{sat} , voltage for carrier speed saturation) a steady state is reached in the bulk of the semiconductor. In this case all the carriers drift during a short time $t_{dr} \ll \tau_0$ and are accumulated on the layer interface. The constant concentration of carriers n_d is established in the whole bulk of the semiconductor, which corresponds to the condition $dn/dt = 0$ in (2).

n_d is obtained from (2)

$$n_d = G_0 t_{dr} \quad (3)$$

and from (3) we can get the conductivity of the depleted layer multiplying both parts of (3) by $q\mu$

$$\sigma_d = \frac{qG_0 L_S^2}{U_S} \quad (4)$$

$\sigma_d = 10^{-10} \Omega^{-1} \text{ cm}^{-1}$ for values $U_0 = 10^2 \text{ V}$, $G_0 = 10^{15} \text{ cm}^{-3} \text{ s}^{-1}$, $L_S = 2 \times 10^{-2} \text{ cm}$. All calculations are made for unit square. Assuming the current in semiconductor active layer resistance of semiconductor will be

$$R_S = \frac{1}{\sigma} L_S = \frac{U_S}{qG_0 L_S} \simeq 2 \times 10^8 \Omega$$

when the thickness of the layer of LC is $L_{LC} \simeq 10^{-3} \text{ cm}$ and $R_{LC} = 10^{-3} \text{ cm} \times 10^9 \Omega \cdot \text{cm}^{-1} = 10^6 \Omega$. Hence it is clear that in this regime the necessary condition $R_S > R_{LC}$ for IC functioning holds in the dark state.

The input image causes the photogeneration of carriers in semiconductor which drift into the bulk of semiconductor and are accumulated on the interface of layers. The carriers accumulated screen the field in semiconductor and redistribute it on the LC layer. The equations which describe the distribution of voltage on the layers are of the form :

$$C_{LC} U_{LC} = C_S U_S + qN_{Sr} \quad (5)$$

$$U_0 = U_S + U_{LC} \quad (6)$$

$L_d \ll L_{LC}$, L_S and hence we neglect the voltage distributed on the dielectric layer. For the LC layer voltage we have :

$$U_{LC} = \frac{C_S}{C_{LC}} U_0 + \frac{qN_{Sr}}{C_{LC}} \quad (7)$$

C_S , C_{LC} are the geometrical capacities of semiconductor layer and LC layer respectively, $N_{Sr} = N_{S0} + N_{SPh}$ the surface density of carriers, $N_{S0} = n_0 L_S + G_0 L_S t_i$, surface density of carriers, determined by the initial concentration of carriers and the dark current of termogeneration of semiconductor $N_{SPh} = G_{Ph} L_S \Delta t_{Ph}$ is the value of the surface density of carriers, created with time Δt_{Ph} by the influence of the input image, where the speed of photogeneration current is G_{Ph} . Taking into account N_{S0} (7) takes the form :

$$U_{LC} = \frac{C_S}{C_{LC}} U_0 + \frac{qn_0 \cdot L_S}{C_{LC}} + \frac{qG_0 L_S t_i}{C_{LC}} + \frac{qG_{Ph} L_S \Delta t_{Ph}}{C_{LC}}. \quad (8)$$

The image registration time is determined in the structures of semiconductor by the carriers drift time in the semiconductor :

$$t_{dr} = \frac{L_S^2}{\mu E_S}. \quad (9)$$

For silicon with values

$$L_S \sim 2 \times 10^{-2} \text{ cm}, \quad U_S \sim 10^2 \text{ V}, \quad t_{dr} \sim 10^{-9} \text{ s}.$$

This is the shortest time, needed for the exposure of an image. The charge created by the light and the voltage redistribution caused by this charge (electronic image) holds during all the time of pulse action. The reaction of LC and hence, the forming of image takes place during time needed for the development of effects in LC under the influence of stored redistributed voltage (regime of delayed displayment). So the exposure time in the IC of this type is not limited by the inertia of LC. This time depends only on the photosensitive part of IC. The IC works during the time of the transition (instationary) process, while applied pulse of the voltage. After some time which is determined by the time of screening of the field by the termogeneration current, the stationary state is established and IC stops working. So the working regime of IC is the dynamic one. Which implies the necessity of feeding IC with the pulse voltage. The duration of the pulse must not exceed the time of the stationary state establishing. This time can be calculated from the field screening condition (8) where $U_S = 0$, $U_{LC} \approx U_0$, $G_{Ph} = 0$ and $(C_S/C_{LC}) U_0$ neglected :

$$t_{scr} = \tau_0 \left(\frac{N_{Sm}}{N_{S0}} - 1 \right). \quad (10)$$

Here $N_{Sm} = C_{LC} U_0/q$ is the maximally possible surface density of accumulated carriers, which screen all the field of semiconductor.

$N_{S0} = n_0 L_S$ the initial surface density of carriers determined by the initial concentration n_0 , τ_0 is the life time. For silicon, if $\tau_0 \sim 10^{-4} \text{ s}$,

$$n_0 \sim 10^{12} \text{ cm}^{-3}, \quad L_S \sim 2 \times 10^{-2} \text{ cm},$$

$$L_{LC} \sim 10^{-3} \text{ cm} \quad \text{the} \quad t_{scr} \sim 3 \times 10^{-3} \text{ s}.$$

So, the duration of voltage pulse is defined by the condition $t_{imp} < t_{scr}$. We can get the threshold sensitivity from (8) were the first 3 members define the value of the dark state voltage on the LC layer

$$U_{dark} = \frac{C_S}{C_{LC}} U_0 + \frac{qn_0 L_S}{C_{LC}} + \frac{qG_0 L_S t_i}{C_{LC}}. \quad (11)$$

For the transition to the nematic state we must redistribute the voltage $U_{\text{SW}} = U_{\text{N}} - U_{\text{dark}}$ on the LC layer. This voltage is defined by the light influence

$$U_{\text{Ph}} = \frac{qG_{\text{Ph}} L_{\text{S}} \Delta t_{\text{Ph}}}{C_{\text{LC}}} = \frac{qN_{\text{SPh}}}{C_{\text{LC}}}. \quad (12)$$

The value threshold energy is equal to the energy of the radiation, which forms N_{SPh}

$$E_{\text{thr}} = \gamma h\nu N_{\text{SPh}} = \gamma h\nu \frac{C_{\text{LC}} U_{\text{Ph}}}{q} \quad (13)$$

where γ is a coefficient of internal photoeffect, is a

energy of light quant. If $\gamma \approx 1$, $h\nu \sim 10^{-19}$ J, $C_{\text{LC}} \sim 10^{-9}$ F and U_{SW} is taken ~ 20 V than $E_{\text{thr}} \approx 10^{-8}$ J/cm². With the suitable frequency of voltage pulse we can reach the following regime : the image formed during only one pulse has no time to relax by the time of the following pulse through the electric image is formed and relaxes with every voltage pulse. In this case a stationary image in LC is observed, which corresponds to the sum of all pulse images.

IC on the base structure of semiconductor-dielectric and LC type owing to its functional possibilities and easy technologic have prospects in optical data processing systems.

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