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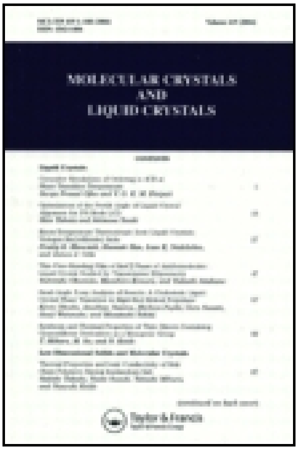

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New Simple Model of a Liquid Crystal Light Valve

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New Simple Model of a Liquid Crystal Light Valve†

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A liquid crystal light valve, using a heterojunction indium oxide/silicon of high resistivity (10,000 Ω.cm) and based on the cholesteric-nematic transition is described. The characteristics of this device are determined: optimum voltage to be applied to the cell in order to produce the cholesteric-nematic phase change, incident light power sensitivity, spectral response, rise and decay times. It has been shown that this light valve has an incident power sensitivity of less than 10 μW.cm^{-2} which passes through a maximum for an incident wavelength of 0.8 μm. This valve can be used in the near infrared; rise times of a few tens of ms are obtained.

INTRODUCTION

There are numerous types of display devices based on the control of an electrooptic medium by a light sensitive layer; these devices usable for optical data processing and projection display can include electrooptic media such as Pockels crystals, ferroelectric ceramics or liquid crystals. In the latter case the light valve consists of two transparent electrodes and between them a photosensitive layer (usually a high resistance photoconductor) in series with a liquid crystal as shown in Figure 1. In the dark the electric field applied to the sandwich drops essentially across the photoconductor. With a write-in light charge carriers are generated in the photoconductor by incident photons; its resistance decreases, the electric field increases across the liquid crystal and can therefore produce electrooptic effects corresponding to substantial optical changes such as DSM or field effect on twisted nematic or cholesteric-nematic phase transition.

In real-time light valves, i.e. those which are read-out during the write-in

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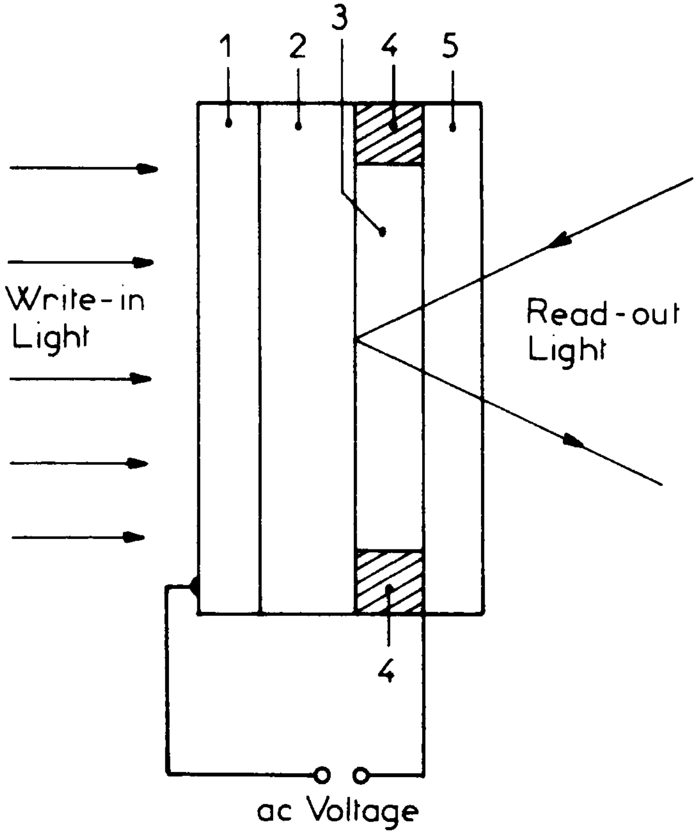

FIGURE 1 Schematic of a light valve: (1) conducting electrode (or In_2O_3 film), (2) photosensitive element, (3) liquid crystal, (4) spacers, (5) conducting glass electrode.

step, the photosensitive material must be protected from the read-out light influence. This can be achieved by an optical blocking layer between the photoconductor and the liquid crystal. Currently the photosensitive medium and the blocking layer consist respectively of a CdS photoconductive film and a Cd Te layer;[1,2] in fact such a device forms a heterojunction photodiode and the current flow is due to the separation of charge carriers (electrons and holes) by the high electric field in the depletion layer. Another possibility is to use a photoconductor having a convenient absorption coefficient to reduce sufficiently the intensity of the actinic components of the read-out light with respect to that of the write-in light, for example selenium[3] (or As_2Se_3)[4] which is photosensitive at wavelengths shorter than 0.56 μm. Recently an image converter using a combination of silicon-SiO_2 and of cholesteric liquid crystal has been described.[5]

It is the purpose of this paper to describe a simple liquid crystal valve con-

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sisting of an indium oxide/silicon heterojunction. It is based on the electric field induced cholesteric-nematic phase transition, from scattering focal-conic texture to clear nematic state, which has a sharp threshold and is quite fast: in fact recovery times of 60 μs have been reported[6] for certain mixtures. With read-out light of wavelengths shorter than 0.55 μm, this device does not require an optical blocking layer, due to the high absorption coefficient in this wavelength range. In addition the sensitivity of this photodiode being maximum at 0.8 μm, it can be used in the near infrared.

EXPERIMENTAL

The device is schematically represented in Figure 1. The photosensitive switching element is an indium oxide (In_2O_3)/silicon heterojunction: a 0.2 μm thick In_2O_3 film (1) is sprayed at 500° C on a polished monocrystalline N-type silicon wafer (2) having a 10 000 Ω. cm resistivity and a thickness of about 200 μm (heterojunctions In_2O_3/Si are currently used as solar cells[7] and the advantages of such a structure are discussed below). A thin (about 10 μm) layer of liquid crystal (3) is sandwiched between the silicon wafer (2) and a conducting glass electrode (5). An ac voltage (or square wave) is applied between the In_2O_3 film and the conducting glass electrode. The alignment of the liquid crystal is obtained by oblique deposition of silicon monoxide layers on the glass electrode and on the silicon wafer. The cell area is of about 5 cm^2.

Various liquid crystals were tested, mostly mixtures of a high positive dielectric anisotropy nematic product (1132 TNC from Merck, K15 from BDH) and a cholesteric substance (cholesteryl nonanoate CN, cholesteryl oleyl carbonate COC, . . .). The choice of a mixture results from a compromise: in fact fast speeds are attained[6] with high concentrations of cholesteric; these mixtures have small pitches P giving for long wavelengths weak scattering and high critical voltages V_c since V_c is proportional to P^{-1}.[8] As an example the transition from the focal conic texture to the nematic state appears in a 13 μm thickness cell respectively at about 18 volts for a mixture of 1132 TNC and cholesteryl nonanoate (8% by weight); with a mixture of K15 and COC (33%), critical voltages of 60 volts are attained; subsequently, we have used the mixture of 1132 TNC (92%) and cholesteryl nonanoate (8%), the pitch of which is 3.7 μm.

The performances of the device were easily determined by using a Leitz microscope in reflected light mode: the cell is placed on the microscope stage and the In_2O_3 side is irradiated with a monochromatic "writing light" coming from a monochromator and filtered through 3 cm of deionized water in order to avoid thermic effects; the power of this incident light is measured with a thermopile radiometer. The liquid crystal side is illuminated through the conducting glass electrode by a monochromatic (0.49 μm) normal-incident-light ("read-

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out light"); its wavelength was chosen to make silicon insensitive to it as will be seen below. The light scattered by the liquid crystal impinges on the microscope photomultiplier, the anodic signal of which is registered on a X-Y recorder. When a sufficiently high voltage is applied to the cell the transition from the scattering focal-conic texture to the clear nematic state takes place and the recorder deviation corresponding to the light variation on the photomultiplier is taken as a relative response of the device; its variations are determined for various parameters (applied voltage, frequency, writing light wavelength and power, . . .).

RESULTS

At first the voltages V_d and V to be applied to the cell in order to produce the cholesteric-nematic transition in the dark ($P_{WR} = 0$) and under illumination for a given writing power P_{Wr} respectively were determined. As mentioned above these voltages depend on the used cholesteric-nematic mixture since the critical voltage V_c of the cholesteric-nematic phase change is determined by characteristics of the product (dielectric anisotropy, pitch and elastic constant), but the voltages V_d and V vary also with the writing power P_{Wr} and the voltage frequency f. An example of these variations is given in Figure 2 for the mixture of 1132 TNC and cholesteryl nonanoate (8%) and for a 13 μm thick layer, but as a general rule a similar behavior was observed for other tested mixtures. These curves show that these voltages decrease for a given frequency when the writing power increases. For the high values of P_{Wr}, the voltages V are practically independent of the incident power and also of the frequency. At a given power, voltages V raise with frequency.

Fraas *et al.*[9] have analyzed the behavior of a heterojunction diode display and have described the photosensitivity of this structure in terms of the depletion-width photocapacity of the diode. If we take, as these authors, in a first approximation (neglecting the series resistances) the equivalent circuit for the ac light valve shown in Figure 3, the voltages V_d and V are given by

$$V_d = V_c\left[1 + \frac{Z_{sd}}{Z_l}\right] \quad V = V_c\left[1 + \frac{Z_s}{Z_l}\right]$$

where Z_{sd} and Z_s are the impedances of the In_2O_3/Si heterojunction diode in the dark and in the light respectively and Z_l the impedance of the liquid crystal.

At a given frequency, Z_s drops for an increasing writing power, due to the charge carrier generation by the writing light and to the correspondent photocapacity increase. For high powers ($>$ 1.5 to 2.0 mW. cm^{-2}) the impedance Z_s is so low that the whole voltage V is applied to the liquid crystal layer. The value of V thus determined must be practically equal to the critical voltage V_c

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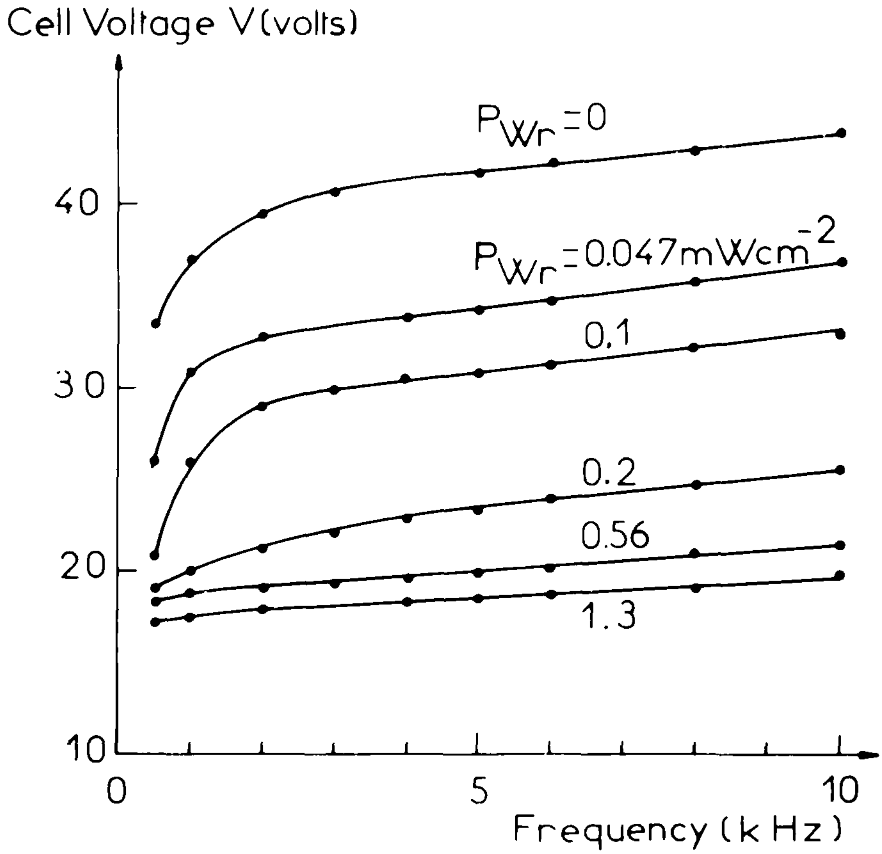

FIGURE 2 Variation of cell voltage V producing the cholesteric-nematic transition vs the frequency f for various writing powers P_{Wr} (mW.cm^{-2}); wavelength of writing light: 0.8 μm; mixture of 1132 TNC (92%) and CN (8%); cell thickness: 13 μm.

of the cholesteric-nematic transition as has been verified by measuring the voltage V_c for a 13 μm thick layer of the mixture between two conducting glass electrodes only. It can be seen from Figure 2 that for these high intensities the switching ratio, which is the ratio between the currents in the light and in the dark $I_{light}/I_{dark} = Z_{sd} + Z_l/Z_s + Z_l = V_d/V$ tends towards a limit of about two.

The variation of voltages V with the frequency is rather complex. Recombination phenomena between the charge carriers play an important part, as shown by Fraas *et al.*:[9] the recombination time is independent of the frequency f, but the number of hole-electron separations is proportional to f; this produces a photocurrent proportional to f as is also the capacitive dark current. Thus the switching ratio, ratio between both currents, must be independent of the frequency which is an important advantage for the applications. As found

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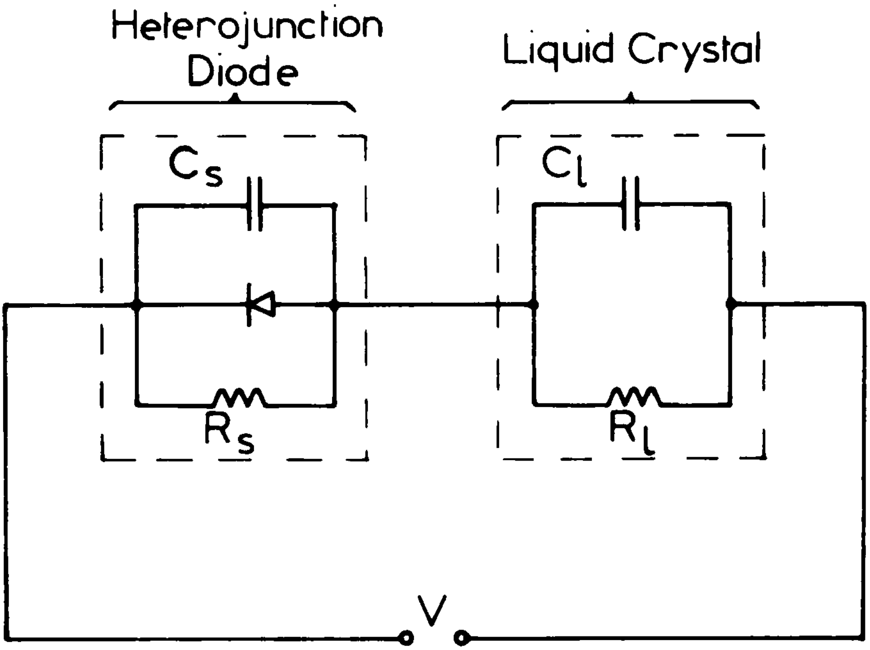

FIGURE 3 Simplified equivalent circuit of the light valve: Z_s and Z_l represent the impedances of the heterojunction diode and of the liquid crystal.

by the authors mentioned above we have observed that it is also the case with our valves in the range 1–10 kHz at various writing powers.

Curves such as those of Figure 2 help to choose the light-valve working conditions (voltage V and frequency f for a given writing power P_{Wr}). In Figure 4 the variations of writing power sensitivity are shown for various values of the voltage applied to a 13 μm thick cell. It appears that a sensitivity of less than 10 μW. cm^{-2} can be easily obtained with this light valve at a writing light wavelength of 0.8 μm. It must be noted that a change of the working conditions can modify the response times as mentioned below.

The spectral response of the device has also been determined by varying the writing light wavelength at constant incident power. An example of spectral response is given in Figure 5 which shows that the sensitivity is maximum at 0.8 μm and about equal to 40% of the maximum value at 1 μm. The shape of this response curve explains the cell insensitivity to read-out light ($\lambda = 0.49$ μm); its wavelength could be increased without difficulty up to 0.55 μm since the absorption coefficient of silicon at this wavelength is of about 10^4 cm^{-1} and consequently the light is absorbed in a very thin layer (a few μm) near the surface. Such a structure can therefore be used in the near infrared: the In_2O_3

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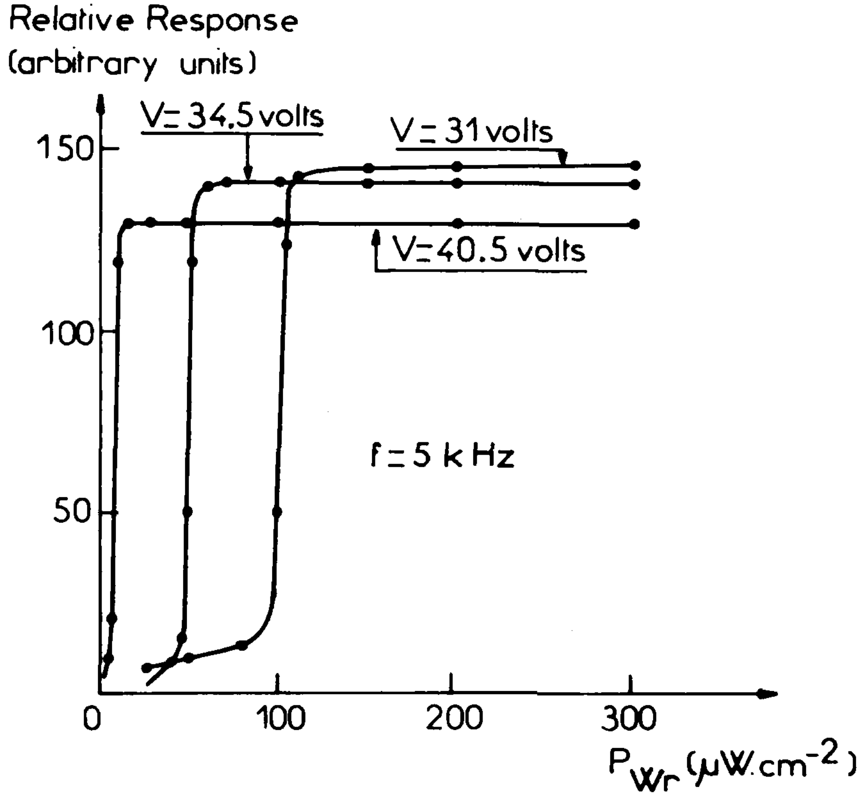

FIGURE 4 Variation of the light valve response vs the writing power for various cell voltages; wavelength of writing light: 0.8 μm; mixture of 1132 TNC (92%) and CN (8%); cell thickness: 13 μm.

layer transmission is nearly constant and equal to 90% for a range of 0.45 to 1.5 μm; furthermore due to its high (≈ 2) index of refraction it provides an antireflection coating. Figure 6 shows a photograph of the image obtained by projecting on the In_2O_3 film a panel of five electroluminescent diodes emitting at 0.93 μm.

The contrast ratio and the spatial resolution have been determined for a 8 μm thick cell. As mentioned by several authors[9,10] a better image uniformity is obtained with higher frequencies of the applied voltage. For a writing light wavelength of 0.75 μm and a square wave frequency of 20 kHz the contrast ratio is 10:1 and the spatial resolution achieved in the same experimental conditions is 20 lines/mm. By adding to the liquid crystal a low (≈ 1%) percentage of a pleochroic dye an improvement of the contrast ratio of up to 18:1 has been obtained.

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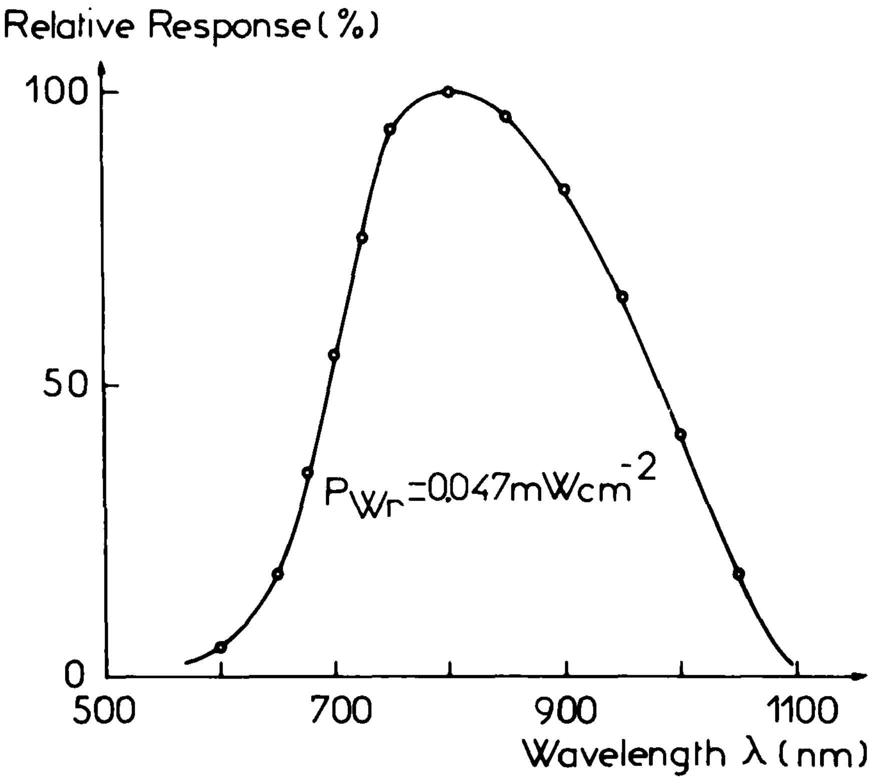

FIGURE 5 Variation of the light valve response vs the writing light wavelength for a mixture of 1132 TNC (92%) and CN (8%); cell thickness: 13 μm.

We have also studied the response times of the light valve. The processes of alignment or realignment of molecules when an electric field is applied or removed are rather complex, depending particularly on the presence of strong wall forces. The expressions giving the rise and decay times of the cholesteric-nematic transition[6] show that they decrease with an increasing electric field. In our experiments, the response times of the light valve are determined by displaying the anodic signal of the photomultiplier on an oscilloscope screen. We have reported in Figure 7, an example of rise time variation as a function of the writing power for two voltages of the same frequency. It appears that the rise time decreases drastically when the writing power and the applied voltage increase, in keeping with the results of other authors. For a given voltage the rise time increases with the frequency at low writing powers due to the lower voltage applied to the liquid crystal layer (see Figure 2). At high powers the whole voltage V is practically applied to the liquid crystal independently of the

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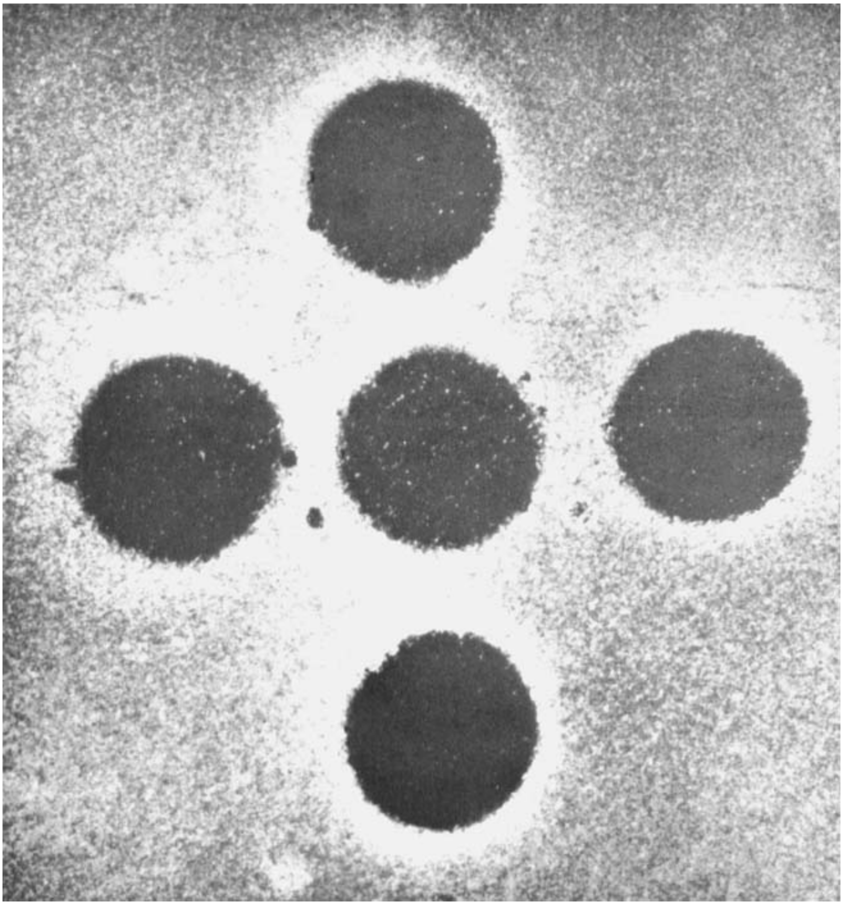

FIGURE 6 Photograph of the image of an electroluminescent diode panel.

frequency; in this range a plot of reciprocal time rise vs E^2, E being the electric field, is linear as predicted by the above mentioned relations.[6] Rise times of a few tens of ms are easily obtained. Turn-off times of the device are, as a general rule, longer than rise times. They depend on the recombination or detrapping phenomena. If the recombination time is short, the decay time is governed by the detrapping rate and must be independent of the incident light power.[10] We have observed that decay times decrease when the frequency raises and tend towards the same value for frequencies of the order of 10 kHz. Decay times of less than 100 ms have been attained.

In conclusion, the light valve described has the following characteristics: a power sensitivity lower than 10 μW. cm^{-2} for a writing light wavelength of 0.8

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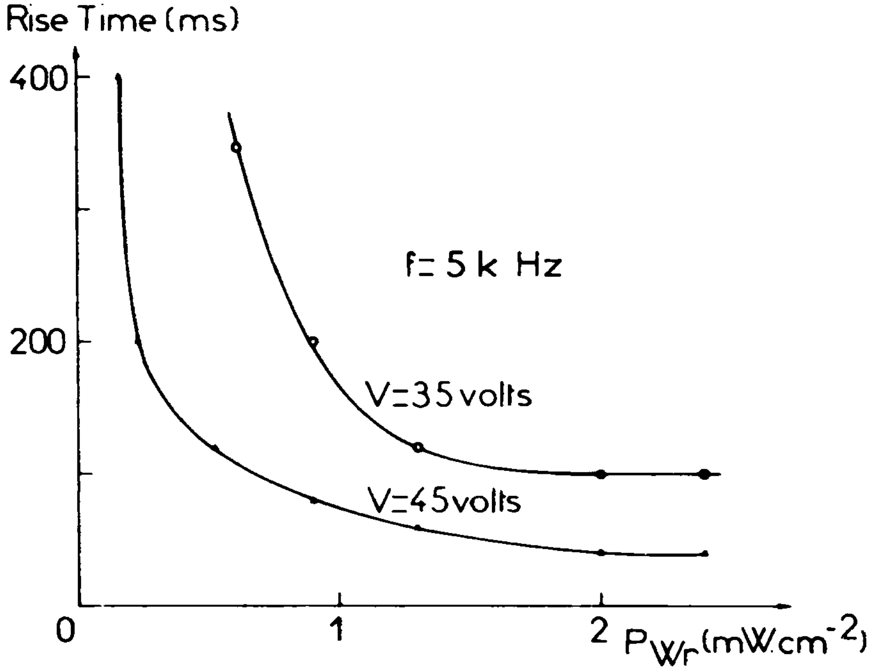

FIGURE 7 Variation of the rise time vs the writing light power for two cell voltages: wavelength of the writing light: 0.8 μm; mixture of 1132 TNC (92%) and CN (8%); cell thickness: 13 μm.

μm, a contrast ratio of up to 18:1, a spatial resolution of 20 lines/mm; in addition it can work in the near infrared.

In order to improve the time response,[11] we intend to use silicon of much higher resistivity than the one employed for this device.

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