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Large liquid-crystalline displays addressed by vitreous varistor switches

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Guest–host LC dot matrix displays with hundreds of lines and columns and with pixels of square millimetre size can be addressed by means of an electronic matrix consisting of novel varistors sandwiched of only three layers, Al–SiO_x–Al. These can be vacuum-deposited through our re-usable stencil masks on cold glass plates (hanging face downward) in one pumpdown, with no dust problem. Square metre sized monolithic display panels become possible in combination with our novel step-and-repeat vacuum deposition of many monomodules side-by-side, employing a simple stepping mechanism inside an enlarged bell jar. This promises to become a very cost-effective new technological path towards wall panel television receivers.

1. Introduction

The most prominent application of liquid crystals in the near future will be flat colour TV in the home. The present 700 million tubular TV sets in the world with a combined display area of about 100 km^2 await replacement by our electronically addressed, sunlight or fluorescent lit flat colour TV panel [1]. Japanese pocket sized LC colour TV receivers have already reached tube quality; briefcase sized LC colour TV sets were being prototyped at a global research and development investment of U.S. \$200 million in 1987. However, the next step, fabrication of 0·5 or even 1 m^2 sized wall panel TV receivers will be much harder to implement, and is the subject of the present investigation.

At present the best technological path toward intermediate sized electronic LC matrices, used by most competing corporations worldwide, is plasma assisted chemical vapour deposition of α-silicon films and TFT gate insulator films on glass panes up to 20 × 30 cm in area, at 350–450°C, using modified production line sputtering machines. New ways of applying photolithographic techniques to such large areas are being found. The requisite large photomasks are made by a step-and-repeat technique (the stepper costs \$1·5 million§). Nevertheless, we feel that these methods will not be usable to produce 1 m^2 sized displays, due to the low yield. Even in class 100 cleanrooms there are too many dust particles which fall on to a 1 m^2 sized substrate during the week-long processing, creating punctures in the films. Our proposed process (fresh faced substrate hanging downward in a one pump-down high vacuum for 18 h, no insulator films at all) does not have this problem, as we shall see.

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§ We could build a stepper for 1 m sized photomasks, with 3 μm accuracy, for about \$100 000.

0267–8292/89 \$3.00

Attempting to circumvent these difficulties, in 1982 we proposed ways to compose very large LC-TFT displays from small monomodules [2], but these schemes were either too complicated (low production yield and high cost), or would not avoid black grids of the gaps between adjacent modules, which disturb the vision. This induced us to investigate the possibilities of monolithic active matrix-addressed LC displays by way of preliminary scouting experiments. For example, for cost reasons, 1 m^2 sized soda lime glass panes (window glass) will have to be used, borosilicate or aluminosilicate panes being too expensive. During processing, these large glass panes must presently be cycled between room temperature and 400°C. Being supercooled viscous liquids whose viscosity decreases exponentially with temperature, they creep and warp, so that unstrained parallel spaced, giant sized LC cells are very hard to fabricate from them in reasonable yield. One way to prevent warping suggested by us [3] is to float the glass panes on pans filled with liquid tin during annealing. A better way would be to find processes which need annealing temperatures of only 250°C or less.

2. Total systems concept

If new technological paths are sought towards realizing an imagined device, clear, detailed concepts of what is needed are essential. Our concept to address a flat TNLC TV panel in a line at a time fashion alternating from an upper and a lower shift and storage register, with additional signal storage at each pixel element for the frame time using TFT switches, set the present stage in 1972 [1, 4]. In dot matrix displays, an electronic switch in series with each LC element steepens the B–V curve of the liquid crystal, thus suppressing crosstalk. In principle, both three terminal and two terminal threshold devices could be used. Since we found it difficult to fabricate three terminal TFT matrices on 1 m^2 sized window glass uniformly, whereas we have now found it easy to prepare two terminal varistor switches (see figure 1), we initiated this research programme on varistor matrices, even though these are not as good as TFTs with respect to grey scale.

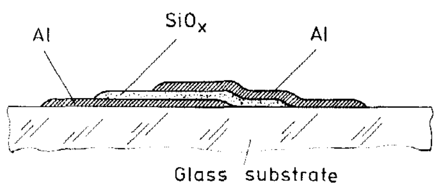

Figure 1. Varistor switch, cross section. Active area 30 × 30 μm, SiO_x thickness 60 nm.

The quality of a varistor is expressed by m in the equation

$$I = AV^m$$

for its current–voltage curve which approximates the real exponential function

$$I = I_0 V \exp \beta V^{1/2}.$$

Vacuum deposited thin film varistors have m values from 5 to 13, in commercial ceramic ZnO pellet varistors an m of 50 is achieved, whereas the ideal step function varistor would have infinite m. In a theoretical analysis of addressing a varistor matrix [5] we conclude that varistors with m = 6 and a threshold of 20 V will suffice for suppressing crosstalk in a 600 line matrix, if a waveform specially developed by us is used [5]. Analysis shows that in these capacitively driven field effect displays the capacitance of the LC pixel electrode must be much larger than the parasitic capacitances of the layered varistor switch, and of the *XY* crossovers. Therefore, we fabricate our varistors, and our *XY* busbar crossovers, as small as our metal mask technology permits, whereas our pixel LC electrode capacitances are made as large as the current handling capability of our varistors allows. This favours large pixel, large area displays, in contrast with the conditions with current α-silicon photolithographic techniques which favour small, high resolution displays.

Other design features of the envisioned flat colour TV panel proposed earlier by us, such as rear illumination by daylight or by white three colour fluorescent lamps through red–green–blue (RGB) absorption filter mosaics, are already in the marketplace. Incidentally, RGB *interference* filter mosaics (multiple MgF_2–ZnS films) which could be vacuum deposited in the same run as the electronic matrix and would give excellent colour rendition, were proposed by us before [6], but never implemented. With RGB filters three times as many pixels are needed than for black and white TV.

Colour LC TV with only the number of pixels for black and white TV is possible with a new variant. Time sequential RGB rear illumination from three alternating RGB lamps, employing fast switching, ferroelectric LCs [7] at triple frame rate, even without active matrix addressing, saving the factor three in the number of pixels. However, this would no longer be compatible with present TV norms and would require excessive external electronics. Grey scale is not easy to obtain. The power consumption is three orders of magnitude higher, due to the high dielectric constant of these ferroelectric LCs (FLCs), and the narrow cell spacing. If combined with active matrix addressing, it would draw too high a current through the active matrix. Therefore, we stay with nematic LCs. Nevertheless, such FLC schemes pose a serious threat to active matrix addressing, the only defence being to make active matrices for nematic LCs much easier to fabricate, which is our goal.

For active varistor matrix addressing, the guest–host nematic LCs ($\varepsilon \approx 17$) are still the best choice, though they are much slower than FLCs. Grey scale can also be obtained by various methods with varistors, even though this requires more peripheral electronics than the TFT matrix addressing.

3. Experimental

3.1. *Varistor fabrication*

Several two terminal thin film threshold devices were known before, e.g. the back-to-back Schottky diodes, diode rings, m–i–m and n–i–n devices, but they are not easy to fabricate. For a comprehensive review, see Kaneko [8]. Here we concentrate on novel vitreous varistors because of their inherent simplicity (see later). Their exponential current–voltage non-linearity is generated by a combination of Schottky and Frenkel tunnelling of charge carriers, first from the metallic electrode into the depleted vitreous insulator, and then from trap to trap, or from excess metal droplet to droplet, to the other metallic electrode, whereby, in addition, the carrier mobility increases with the applied external field. Since this is a bulk effect, we find that these vitreous varistors are much easier to produce with large area uniformity than other active matrix switches, e.g. TFTs, which depend on surface charging effects which are highly sensitive to processing parameters, and so are hard to reproduce over large areas, especially if vacuum deposited, insulating films are employed [9].

Fujita *et al.* [10] stimulated our activity in this field with their announcement of vitreous ITO–$AsSe_x$–Te varistors which can be vacuum deposited on glass plates at room temperature without post annealing, through only one metal mask. We were able to reproduce these varistors, but there were severe shortcomings not mentioned in [10]:

(*a*) Each time the vacuum system is opened to the atmosphere, highly toxic and evil smelling fumes of hydrides of selenium, tellurium and arsenic are developed by reaction of the humid air with these films. This would be a severe environmental hazard in mass production and therefore must be curbed from the onset.

(*b*) By the annealing, which is required to prepare the LC cell (during polymerization of the edge sealing paste, and during hardening of the LC orienting resin film) these varistors are damaged, they cannot sustain even 100°C. We remedied this by inventing a U.V. hardenable, LC orienting resin film, and by using U.V. hardened LC edge sealing, so that the whole LC cell can now be fabricated at room temperature, with just gentle warming during filling.

However there is a third problem.

(*c*) These varistors are not electrically stable over extended periods, their I–V curves drift!

Deficits (*a*) and (*c*) induced us to abandon these ITO–$AsSe_x$–Te diodes, as alluring as they had seemed at first. In search for a better material we also rejected the reactively sputtered Cr–SiN_x–ITO varistors described by Suzuki *et al.* [11], since they require photolithographic processing to contour the SiN_x and metal films (sputtering through metal masks is not possible). Photolithographic processing is much more prone to defects, and more costly than our one pumpdown vacuum depositions method.

Then we discovered that SiO_x had long been known for its suitability as a vitreous varistor material [12]. SiO_x is a common non-toxic easily evaporated cermet material consisting of excess silicon dispersed in vitreous SiO_2. The granular material can be electron beam (EB) or hot boat evaporated, but then a new charge must be used each time since the x in SiO_x diminishes during vacuum heating, leading to changes in the electrical characteristics of the diodes from run to run. These Al–SiO_x–Al diodes are stable when deposited on glass at room temperature, with $m = 6$, but drift on annealing. A novel finding of great practical importance is, therefore, that we can now reactively evaporate silicon by EB heating in an oxygen atmosphere, or even in air (!), of 10^{-5}–10^{-6} mbar pressure and thereby obtain Al–SiO_x–Al varistors with $m = 7$ (see figure 2). In this case there is no need to discard the unused material after each run, so continuous production is possible [13]. These varistors must be stabilized by annealing at 200–250°C, which will not harm the glass plate.

The pixel layout is shown in figure 3. In the display cell, the thin, flexible upper glass plate carries the Y signal busbars which consist of evaporated narrow titanium links to which the wide, transparent pixel electrodes (made from 2 nm thick titanium films) are connected. The lower, thick glass plate of the display cell carries the titanium scanning X busbars to which the transparent titanium electrode pads are linked via the varistors. In this way, the XY crossover capacitances are kept low. Since the X and Y bus bars are therefore on separate glass plates, separated by 6 μm of liquid crystal, no longer by thin evaporated insulating films, catastrophic XY crossover short circuit defects can no longer occur (which would inactivate one whole line and one whole column). This is a very important design feature which, with TFT matrices,

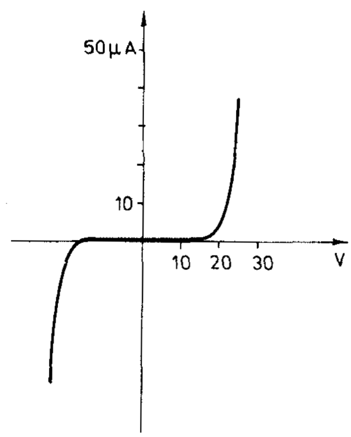

Figure 2. Curve tracer photograph of Al–SiO–Al varistor; threshold voltage 25 V.

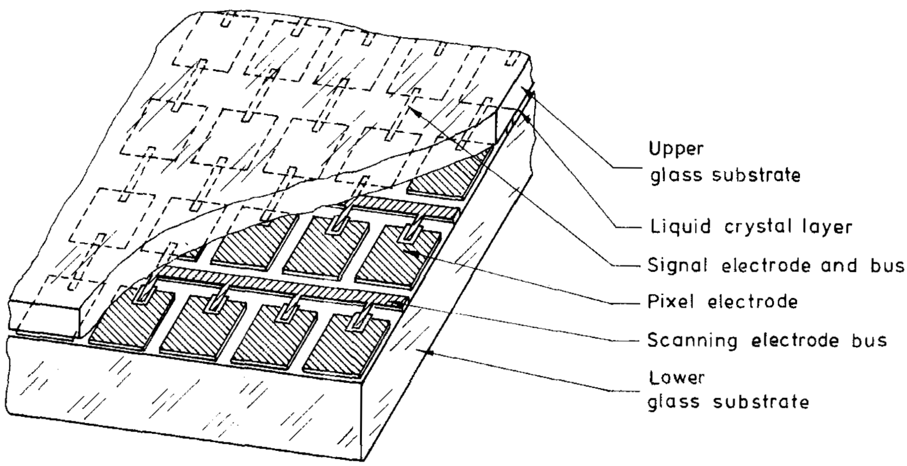

Figure 3. Layout of the varistor matrix. Note the chain structure of the signal bus electrodes, to minimize the crossover capacitances, and the thick basal glass pane.

requires the no crossover, butterfly TFT scheme [14] which is much more complex to realize. The stencil masks employed are our usual gold–cobalt/Invar foils described elsewhere [15]. All depositions proceed in our automated one pumpdown deposition apparatus capable of using up to nine masks, as described elsewhere [2].

3.2. *LC cell fabrication*

Even though the envisioned 1 m^2 sized LC display cell has not yet been implemented, smaller ones were prepared by the same methods to practice for the large ones. The rear glass plate consists of a sturdy, thick (4–5 mm) float glass pane. It holds the X busbars, the varistors and the transparent electrodes. This half of the matrix is finally covered with an overall SiO_x film which prevents galvanic contact with the liquid crystal. (It is interesting to note that, in contrast, with our TFT matrices such SiO_x overall films would shift the threshold voltages uncontrollably.) The oriented resinous surfactant is applied to this film by spraying. Since the SiO varistors can tolerate the heat, the common polyimide surfactant can be used. After hardening at 250°C it is brushed unidirectionally with a velvet covered, motor driven rotating cylinder. (It is interesting to note that during brushing the electrostatic charging does not damage the varistors, whereas it was deleterious for the insulated gate TFTs.) The front glass plate consists of a thin, flexible, 1 mm thick drawn glass pane. It holds the Y busbars and transparent electrodes, a final SiO_x film overall to prevent galvanic contact with the LC, the resinous surfactant film to orient the liquid crystal, and the cell spacers.

After aligning the two superimposed finished cell electrode plates by means of two microscopes placed at opposite corners, the LC cell edges are then sealed with U.V. hardenable resin paste, except for the filling hole at one corner. Then the cell is warmed to 70°C in a large vacuum oven, the liquid crystal is sucked in, the filling hole is sealed and the cell is cooled to room temperature. As is well known, the vacuum created by the strong shrinkage of the liquid crystal presses the two glass plates parallel against each other, despite their waviness, limited by the spacers. The liquid crystal materials presently used are Merck Guest–Host Licrystal ZLI 3532/1 ($\varepsilon = 8{\cdot}7$) and ZLI 3499/1 ($\varepsilon = 17{\cdot}7$) with a black dye. The cell thickness is 6 μm. The cell spacing is maintained with dispersed spherical particles, or with fibre sections; spacers made from photo lacquer are possible.

3.3. *Step and repeat deposition of large active matrices*

Our present system permits vacuum deposition of active monomodule matrices, 120 × 90 mm, with a throw distance of 80 cm through a set of up to nine stencil masks within $\frac{1}{2}$ h, with uniform electronic properties over this area. In efforts to extend this capability to very large electronic displays without having to resort to giant sized vacuum deposition systems and 1 m^2 sized stencil masks, we invented the step-and-repeat vacuum deposition method [16] whereby thin-film matrices of the present small size are vacuum deposited successively side by side with gap free electrical interconnections, by step shifting the large glass substrate in the X or Y direction by one module length or width each time one module deposition is completed, and by automatic repetition until the large matrix is completed. For example, a matrix with 600 lines and columns (full black and white TV resolution), 720 × 540 mm, could be evaporated with our present masks having 100 lines and columns, in 36 steps, requiring 18 h of work by the machine. The requisite vacuum system still has only 80 cm throw distance and the same six crucible EB hearth and mask changing system, only the bell jar now has the shape of a mushroom, its enlarged top containing the large glass substrate mounted on a stepping mechanism (see figure 4). Since this mechanical stepping system cannot tolerate heating, *only our method which permits deposition of matrices on room temperature substrates offers this new, large area capability*. It helps that this large area, thin film electronics does not require very high accuracy, $\pm 3\,\mu$m is good enough. We imagine that in a future factory 100 such machines will work side by side, attended by only a few human workers.

To prove this step-and-repeat principle, we are presently constructing a machine which will deposit four interconnected monomodules (2 × 2) side by side. Since the glass substrate points with its surface downward (no dust can fall on it), and since this surface is cleaned by glow discharging in dilute air before deposition starts, followed by vacuum deposition of a fresh Al_2O_3 film to provide a virgin surface, and since all depositions occur in one pumpdown, this eliminates the need for an expensive, large clean room (but, of course, not for a small one for the following liquid crystal cell

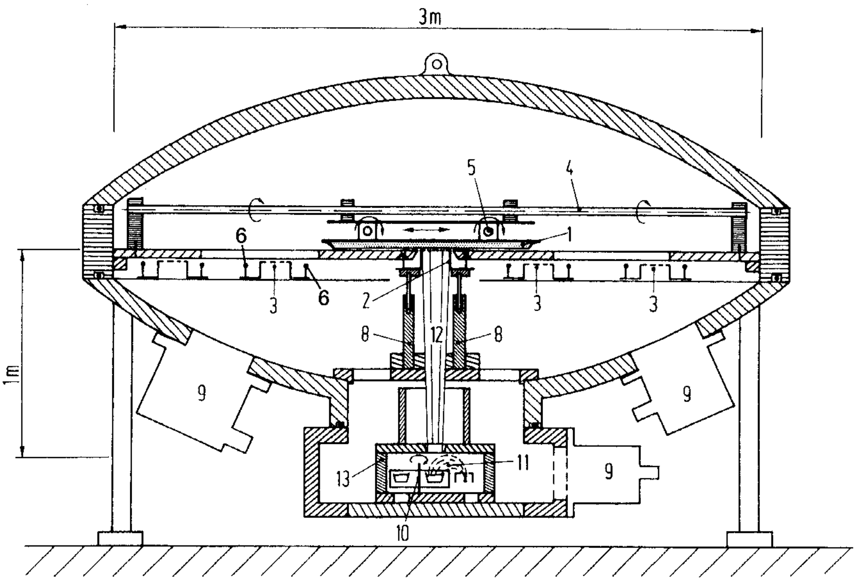

Figure 4. Principle of step and repeat matrix vacuum deposition system. 1, Glass pane substrate mounted below Invar plate; 2, mask frames, in use and in storage; 3, perforated bimetal mask foils; 4, rotating, precision geared rod for *X* shifting, stepper motor driven; 5, rotating, precision geared rod for *Y* shifting, stepper motor driven; 6, ballpin fitting; 7, funnelled socket fitting; 8, stage for lifting and lowering mask frames to and from substrate, stepper motor driven; 9, high vacuum pump; 10, six crucible copper hearth, water cooled; 11, electron beam (10 kV), bent by 180° by magnet (not shown); 12, vapour beam; 13, vapour condenser box, easily cleaned.

preparation). This fabrication method is, therefore, lower in initial investment costs, and in maintainance expenses, by two orders of magnitude compared with the α-silicon TFT matrix methods presently employed by the big corporations.

The objection is often raised that our system is handicapped by the dust particles which are generated inside the bell jar from evaporated films which peel off. This source of trouble has been eliminated long ago by encasing the EB evaporator (which sits at the bottom of the system, see figure 4) into a box made of thick metal plates. This box has a lid with a small slot through which the desired beam escapes toward the substrate. All the other vapours are trapped on the cold metal walls of the box, from which they do not peel since these thick plates do not heat up very much during the operation. Every hundred runs or so they are cleaned by immersion in dilute hydrofluoric acid. We do the same with the stencil mask foils on their frames. Another objection that is raised against our perforated mask vacuum deposition is that at sharp film edges there would be poor step coverage, leading to open circuits. However, since our bimetal masks are mounted such that the pattern defining 3 μm thick hard gold–cobalt film points toward the vapour source, whereas the strongly underetched 50 μm thick Invar foil is magnetically attracted to the glass substrate, the film edges are diffuse and have a sinusoidal slope, which gives good step coverage.

4. Conclusion

This new combination of materials, processes and fabrication methods promises to become a feasible, cost effective technological path towards future production of multi-element liquid crystal displays for wall panel TVs which are larger than present cathode ray tubes; the multi-billion dollar LC application waiting to be conquered.

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