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THE VERSATILITY OF SCANNING ELECTRON MICROSCOPY IN THIN FILM DEVICE ANALYSIS

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Abstract

The versatility of scanning electron microscopy is shown for many stages of fabrication of thin film transistor driver matrices for actively addressed liquid crystal displays. Electron channeling and Schottky barrier charge collection modes allow rapid assessment of silicon crystal quality. The secondary electron mode allows examination of conductor lead crossover integrity. A form of voltage contrast is used on the completed array to monitor performance of the array prior to liquid crystal filling.

Key Words: Electron channeling, charge collection, charging, voltage contrast, thin films, transistors.

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Introduction

Single crystal transistors fabricated on insulator material are used to drive backlit liquid crystal matrix displays. One approach is to laser recrystallize polycrystalline silicon deposited on a quartz substrate. Figure 1, taken from a review of active matrix approaches, shows the basic structure of a picture element.(8)

Our fabrication approach has been to deposit polysilicon on a quartz substrate, pattern it in stripes and cap it with SiO_2 and Si_3N_4 layers, laser recrystallize the polysilicon, and build MOS transistors with self-aligned polycrystalline gates over the single crystal islands. Aluminum lines with insulated crossovers allow the matrix to be addressed from the four edges of the display. A detailed description of the fabrication process is given in reference 5.

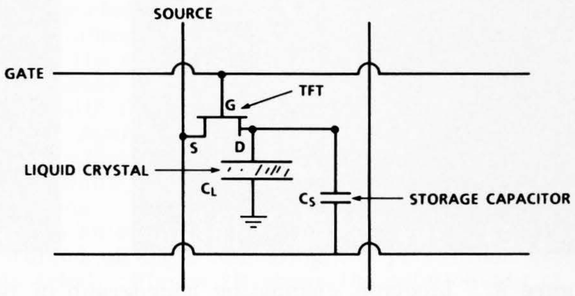


Figure 1A. Thin film transistor-aided LCD picture element equivalent circuit.

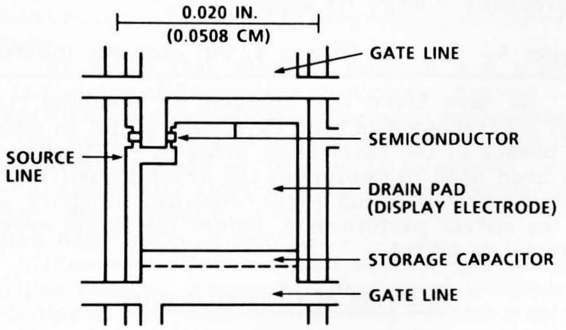


Figure 1B. Drawing of a picture element.

Figure 2A. Round beam scanned along polycrystalline silicon (P) stripe.

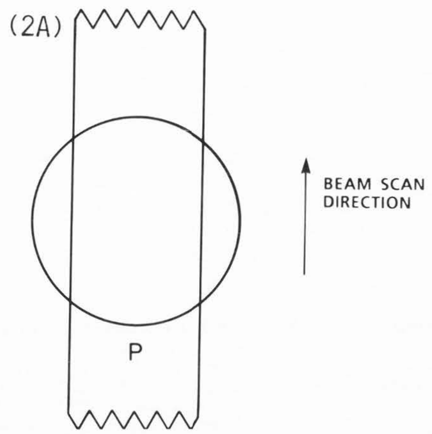
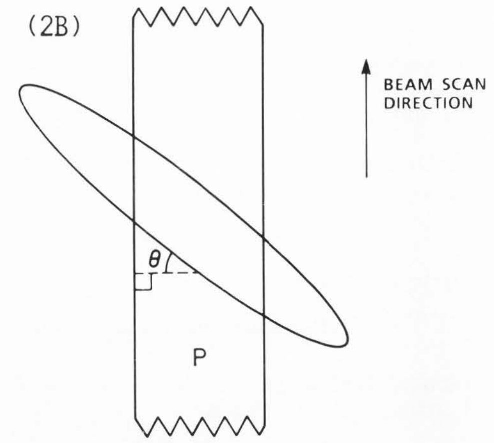
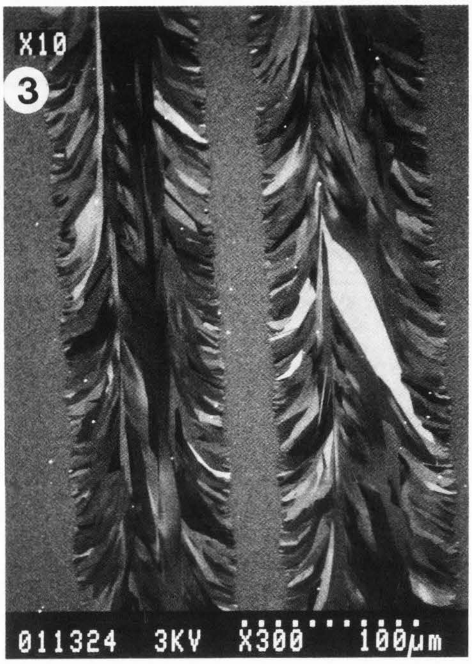
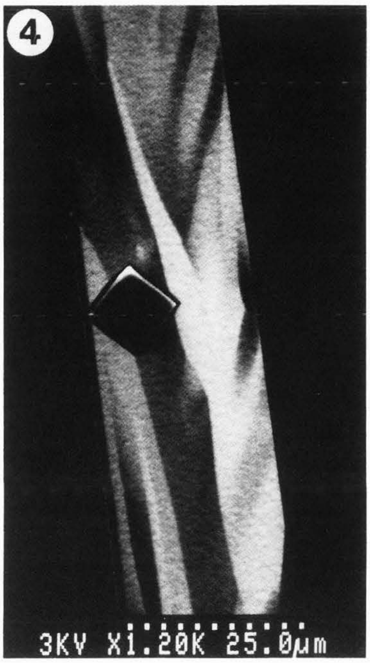


Figure 2B. Angled elliptical beam scanned along polycrystalline silicon (P) stripe.







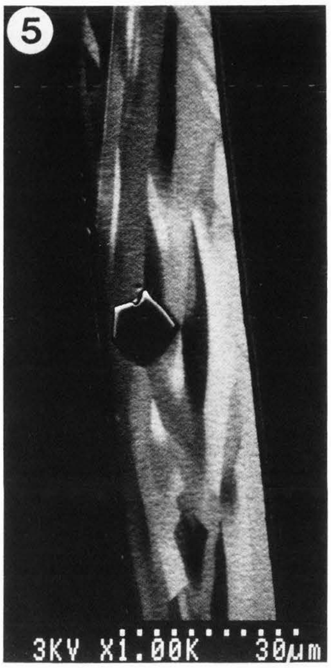


Figure 3. Electron channeling micrograph of two round beam laser scans on unpatterned polycrystalline silicon film.

Figure 4. Electron channeling micrograph of round beam scanned polycrystalline silicon stripe. Note anisotropic etch pit square, indicating (100) film orientation. Grain boundaries intersecting square do not appreciably change its shape.

Figure 5. Same as Figure 4, but etch pit indicates that some boundaries are not low angle boundaries.

We have found that analysis by scanning electron microscopy has been extremely useful in nearly all phases of the fabrication process. SEM analysis has been used to monitor a) the crystal quality after laser recrystallization b) the crossover integrity, and c) the matrix performance, before the liquid crystal material is added.

Analysis of Crystal Quality

Laser scanning of polycrystalline silicon was performed for three different conditions: (a) laser spot (i.e., round beam) scanning of an unpatterned polycrystalline film, (b) laser spot scanning of a thin patterned stripe, and (c) an angled scan of the polysilicon stripes using an elliptical beam. The last condition involved varying the beam ellipse angle relative to the polysilicon stripe (Figure 2).

Transmission electron microscopy had been used to analyze the scanned crystal quality. This entailed coating the scanned material with a polymer, dicing out segments of the quartz substrate- recrystallized silicon-polymer sandwich, placing the segments quartz side down in beakers of hydrofluoric acid overnight and recovering the crystallized silicon-polymer pieces on a specimen grid (5). The grid would then be examined by TEM. While much could be learned about crystal quality with this procedure, the technique was very time consuming and destructive to the sample.

We found that a much more useful technique for scoping the effect of the various laser scan experiments was to use the electron channeling mode of our SEM. Good discussions of electron channeling contrast are given in references 4 and 7. A simplistic but useful description of electron channeling is that, in amorphous materials, primary electron interactions are uniform along the specimen surface, while in crystalline materials, regular lattice spaces can permit some primary electrons to channel relatively deep into the material. When this occurs, both primary backscattered and secondary electron yields are decreased because fewer electrons have the required energy to escape from the material. As the crystal axis is tilted, the yield changes as a function of the effective lattice spacing relative to the beam. In this way, crystal grains having varied orientations show varied intensities.

We did not find it necessary to exclude secondary electron collection (these also carry channeling contrast information). However, due to the low contrast resulting from channeling (< 5%), it was necessary to maximize the signal-to-noise ratio (relatively high beam currents), minimize non-channeling interactions (low beam energy) and minimize the d.c. level of the image signal (brightness control set low, contrast control set high).

It is also extremely important to minimize the amorphous native oxide (3 nm) on the silicon; for this reason the samples were dipped in a 50:1 HF solution just before observation. When this step was omitted, channeling contrast was poor.

There were several advantages of this technique: (a) the recrystallized material could be nondestructively examined intact on the quartz wafer; after examination for the silicon crystal quality, the wafer could be further processed into MOS transistors to correlate crystal quality to device performance (b) analysis of a scanning experiment was accomplished in minutes; less than an hour after the wafer was scanned, the resultant crystal quality could be known, which would then suggest a new experiment. This efficient experiment - analysis cycle allowed rapid progress.

The only specimen preparation, aside from the 50:1 HF dip to improve contrast, was to electrically ground each of the scanned recrystallized silicon stripes to the sample stub, using silver paint. Otherwise, the silicon stripes, electrically floating on the quartz substrate, would charge up and give poor electron channeling contrast.

A representative micrograph of the condition in which a round laser beam scanned an unpatterned polysilicon film is given in Figure 3. It can be seen that the result is large grained crystal material.

A channeling micrograph from a sample in which a round laser beam scanned a patterned polysilicon stripe is shown in Figures 4 and 5. In some areas, the grains are at low angles relative to each other (Figure 4). This was revealed by an anisotropic etch technique in which a round hole patterned in an oxide over the silicon allows the silicon to be anisotropically etched revealing the (111) plane orientation (2). The etch pattern in Figure 4 shows the silicon to have a (100) orientation, and grains intersecting the etch pit do not substantially alter it, indicating a low angle boundary. However, in other areas, typified by Figure 5, the orientation of grains intersecting the etch pit are seen to alter the pit shape, indicating larger angle grain boundaries. Large angle grain boundaries are undesirable for their effect on p-n junctions. Since grain boundaries are pipelines for dopant diffusion, they can alter the p-n junction profile of a MOS transistor, which depends on the properties of a highly doped n+ region adjacent to a lower doped p region (6).

To determine the effect of grain boundaries on the p-n junctions of our thin film transistors, charge collection scanning electron microscopy was employed (a good review of this technique has been given in reference 9). Figure 6 shows a split micrograph, the top frame (6A) showing an electron channeling micrograph of a transistor whose gate and gate oxide have been removed. The bottom frame (6B) shows the charge collection image of the two p-n junctions. One junction is brighter than background while the other is darker than background because the direction of collected current from one junction is opposite that of the other junction.

Figure 6A shows what appears to be several twin boundaries (t) and several grain boundaries (g). The charge collection image in Figure 6B clearly shows that the apparent twin boundaries have no effect on the p-n junctions. This is expected since twin boundaries are coherent boundaries and thus are not sites of enhanced diffusion of dopants.

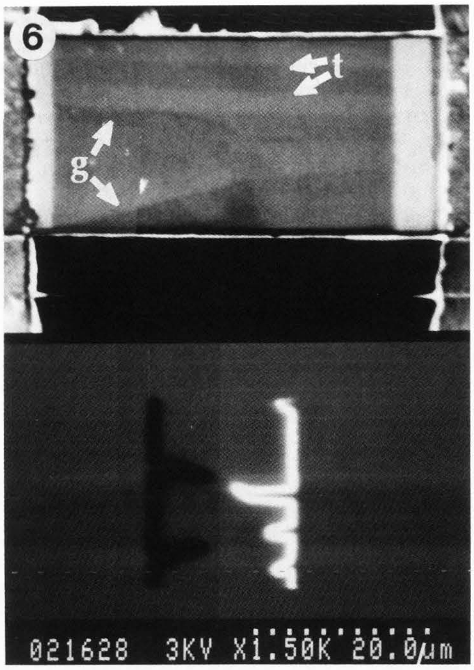
However, the incoherent grain boundaries have resulted in distortion of the p-n junction as a result of the diffusion of the n+ dopant into the lightly doped p channel, via the grain boundaries. The effective channel width of this device is a small fraction of the designed width.

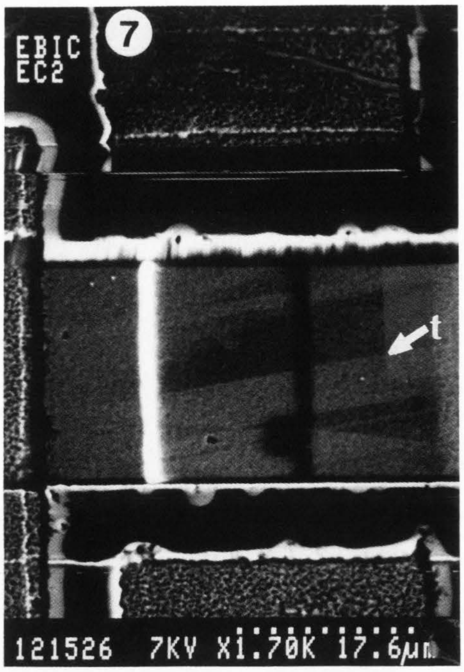
Figure 7 shows an electron channeling micrograph with the charge collection image superimposed on it. Again, it can be seen that some boundaries do not affect the p-n junctions (e.g., twin boundaries) while incoherent boundaries do affect the junctions.

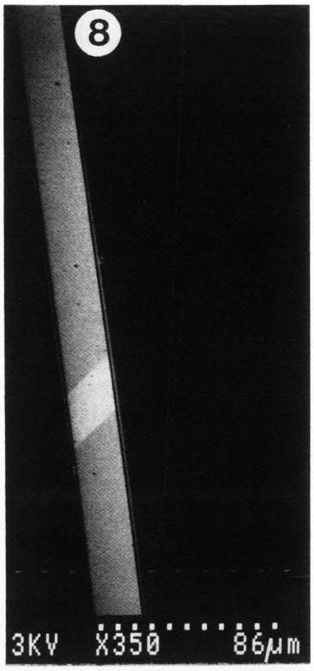
In an effort to eliminate incoherent boundaries, a method of angle annealing the polysilicon stripes was tried. Figure 2B shows the relationship of the stripe, the tilted elliptical beam and the scan direction. The reasoning was that the tilted solidification front would quickly terminate any grain boundaries forming perpendicular to the solidification front. References 3 and 10 contain excellent discussions of grain boundary formation in progressing solidification fronts.

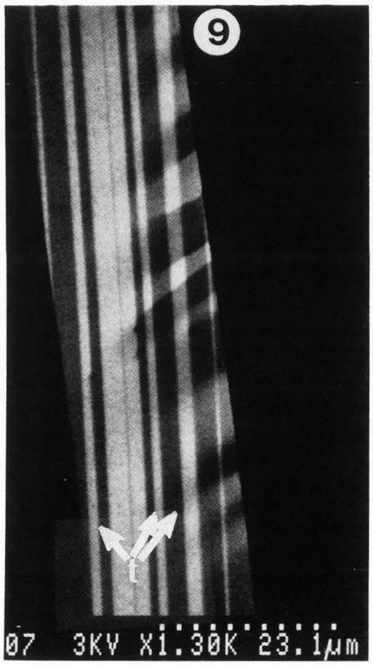
We found that the best material was achieved at tilt angles of 55 degrees or higher. Figures 8 and 9 are electron channeling micrographs representative of the kind of crystal morphology seen using these scan angles. Much of the material is similar to Figure 8, essentially single crystal with occasional twinning. The crystal quality is clearly superior to untilted beam scanned material.

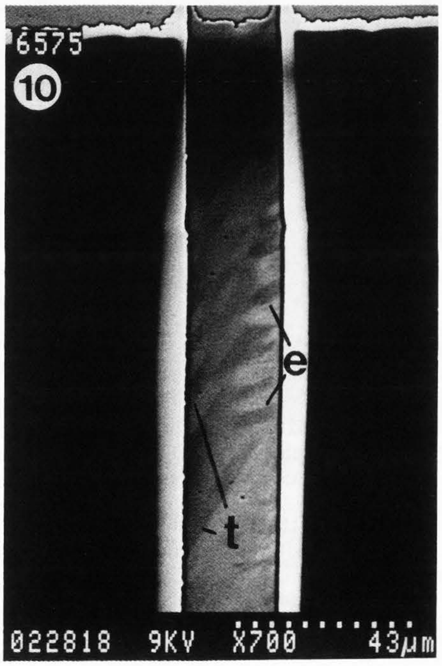
However, other sections of the recrystallized stripes resemble Figure 9. Here there is extensive twinning accompanied by additional crystal structure on the side of the stripe that solidifies last. Because this structure is curved, it cannot be twinning and so was studied further.











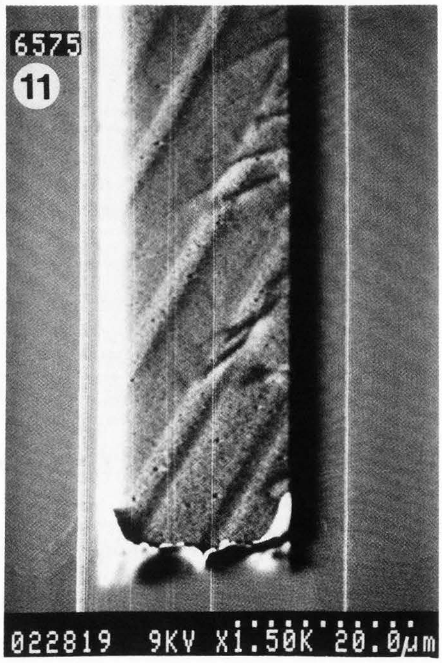


Figure 6. Split screen micrograph A) Upper frame: electron channeling micrograph of recrystallized silicon transistor body, showing twin boundaries (t) and grain boundaries (g). B) Lower frame: p-n junction charge collection micrograph, showing distortion of junctions due to enhanced diffusion along grain boundaries.

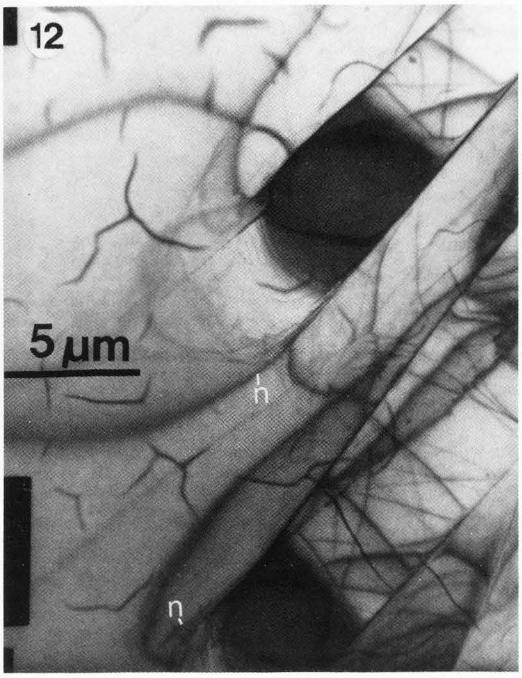
Figure 7. Charge collection image superimposed on electron channeling image of transistor body. Note that junction is unaffected by twin boundary (t) but is distorted by an incoherent boundary.

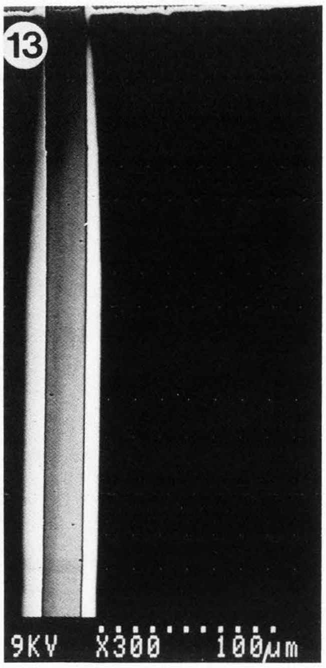
Figure 8. High angle scanned polycrystalline silicon stripe. Note predominantly single crystal material with some twinning.

Figure 9. Same as Figure 8 but with extensive twinning (t) and some additional structure on far edge.

Figure 10. Electron channeling micrograph of angle scanned polysilicon stripes, showing twinning and edge structure.

Figure 11. Schottky barrier charge collection micrograph showing that edge structure represents incoherent boundaries that are electrically active (i.e., lifetime killers).





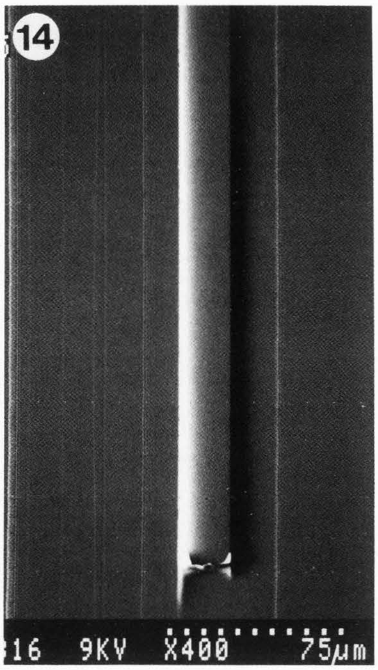


Figure 12. Incoherent low angle boundaries on far edge of angle scanned stripes. Due to coalescence of dislocation networks (n).
Figure 13. Electron channeling micrograph of single crystal material.
Figure 14. Schottky barrier charge collection micrograph of stripe in Figure 13.

Since incoherent grain boundaries are sites for enhanced electron-hole pair recombination, they can be revealed by Schottky barrier charge collection microscopy. In this technique, a metal is deposited on the silicon surface and charge generated by the scanning electron beam interaction is collected by the depletion area in the silicon due to the work function difference between silicon and the metal (for details, see reference 9). The charge collection signal for a metal deposited on perfect single crystal silicon will be a constant signal as the electron beam is scanned across the material. However, at imperfections in the silicon lattice, such as an incoherent grain boundary, electrons and holes generated by the SEM beam can recombine before they are collected. In other words, near crystal imperfections, the lifetime of electrons and holes is shorter than the time required to collect the charges, so these areas appear darker on the Schottky barrier image.

Figure 10 shows an electron channeling micrograph of an angle annealed silicon stripe showing both twinning (t) and the additional edge structure (e). At the top of this micrograph can be seen the edge of a thin film (500 nm) of aluminum coated over the stripe to form the Schottky barrier.

Figure 11 shows the Schottky barrier charge collection micrograph just above the border of the aluminum. Two types of structure are seen: (a) black lines representing decreased charge collection from incoherent boundaries and (b) bands obviously related to the twinning seen in the channeling micrograph. The incoherent boundary image was expected but the twinning banding was not since twinning is coherent. We speculate that the twinning contrast arises from the differing surface state densities of the twins at the silicon-aluminum interface, since it is known that different silicon surfaces have different surface state densities. Electron-hole pair recombination is enhanced at surface states.

We further examined the edge structures seen in Figures 9-11 using transmission electron microscopy. Figure 12 shows a micrograph of these structures, showing them to result from the coalescence of dislocation networks into low angle grain boundaries. These are similar to subgrain boundary initiation sites observed by Pinizzotto (10) in graphite strip heater recrystallized silicon.

Figures 13 and 14 show electron channeling and schottky barrier images, respectively, of single crystal material showing no contrast in either mode.

In summarizing crystal quality analysis, the electron channeling mode, the p-n junction charge collection mode and the Schottky barrier charge collection modes were used to examine the effects of various laser scan experiments on crystal quality and electrical behavior. This analysis allowed us to rapidly optimize our scan parameters to produce recrystallized silicon that is mostly single crystal with some twinning (which is not expected to affect device performance) and minimal subgrain boundaries.

Crossover Integrity

Crossover integrity is crucial and a liquid display matrix of reasonable size and resolution involves a large number of crossovers. Atmospheric pressure chemical vapor deposited phosphorus doped silicon dioxide (PSG) was used as the crossover dielectric because it could be reflowed to minimize step coverage problems for the second metallization layer. The

SEM in the secondary electron mode was used to evaluate various thickness and reflow treatments to optimize the crossovers.

Display Defect Analysis

Figure 1 shows a single picture element from a completed driver matrix. At a display resolution of 50 elements per inch, each square inch of display has 2500 picture elements. It was desirable to be able to test a completed display before building the liquid crystal cell over the driver matrix. This would allow defective matrices to be discarded, thus avoiding the wasted time and effort in completing the display. A method of analyzing the defects was also desired, to understand their cause.

A method of analyzing the driver matrix for defects was developed using a form of voltage contrast. This technique was previously described (1). Since the driver matrix is fabricated on dielectrics such as glass or quartz, specimen charging occurs on the entire structure. By selectively grounding appropriate circuit elements, a number of circuit defects are revealed, including source and gate line open and short circuits. Figure 15, from reference 1, shows a schematic of the setup.

An example of this technique is given in Figure 16 (from reference 1), which shows a voltage contrast micrograph in which all source and gate lines have been grounded. If the driver matrix had no defects, all elements would be expected to be dark (i.e., not charging). However, three defects are apparent in this micrograph, due to their brightness: (a) a break in a source line causing four pixels to charge, (b) an open transistor causing a single pixel to charge up, and (c) a gate line open causing the third gate line from the right to charge up.

Using this technique, a 2500-element driver matrix can be analyzed in minutes. Another advantage is that once a defect has revealed its presence, it can be examined under high magnification to determine its cause. In fact, the dynamic operation of the thin film MOS transistor switches can be observed by grounding the source line of a pixel and switching the gate line on or off. When the gate line voltage inverts the channel of the MOS transistor, the stored charge on the drain pad goes to ground. The initially bright (charging) drain pad now becomes dark.

This technique allows rapid, nondestructive analysis of completed liquid crystal driver display arrays, provided that the accelerating voltage and electron flux of the SEM beam be kept low to avoid damage to the gate oxide of the MOS transistor.

Summary

In our research and development of actively driven liquid crystal displays using recrystallized thin film transistors, the SEM has been a versatile tool both for analysis and quality control. The crystal quality of recrystallized silicon was analyzed using electron channeling and Schottky barrier charge collection microscopy. The p-n junctions were monitored using junction charge collection microscopy. Gate and source line crossover integrity was optimized using the secondary electron mode. Finally, the completed driver matrices were examined using a form of voltage contrast microscopy that allowed quality control analysis of the driver matrices before fabricating the liquid crystal cell. Results from the analysis of matrix defects were used to optimize the fabrication process.

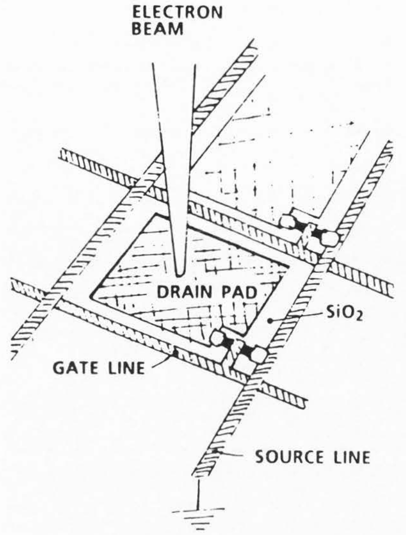


Figure 15. Charge grounding schematic.

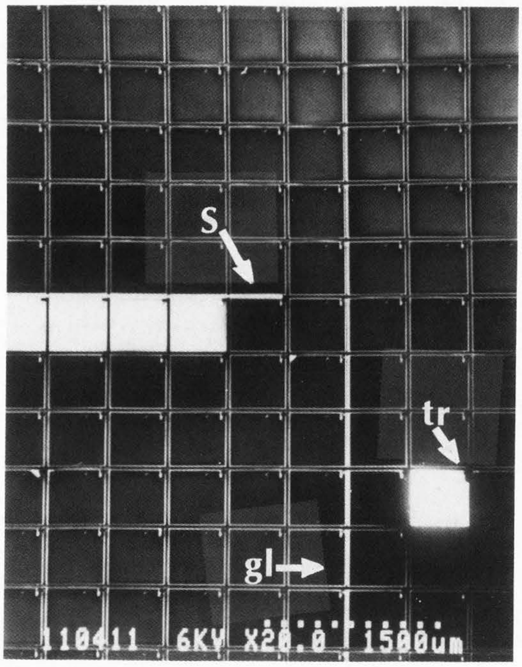


Figure 16. Charging voltage contrast micrograph showing source line break (s), open transistor, (tr) and open gate line (gl).

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Discussion with Reviewers

D.J. Dingley: You have clearly distinguished grain boundaries in polysilicon but have obtained no information regarding the orientations of the grains either side of the boundary. How then do you justify distinguishing some grain boundaries as coherent and others incoherent, bearing in mind that coincidence boundaries are high angle boundaries but are also coherent in that they contain no intrinsic grain boundary dislocations?

Authors: Electron channeling contrast gives no information on grain orientation. We use it primarily as a quick indication of crystal quality since, ideally, one would like to achieve perfect crystallization (which would show no channeling contrast). However, since twin boundaries are not active defects (in terms of electron-hole recombination or enhanced dopant diffusion), we wish to distinguish them from active defects such as incoherent grain boundaries. We do this by means of charge collection microscopy, using p-n junction collection for visualizing enhanced diffusion along incoherent grain boundaries and Schottky barrier charge collection for enhanced recombination at incoherent boundaries.

K.A. Jenkins: The damage of MOS gate oxides by long exposure to high energy electrons is pointed out in the paper. Yet the micrograph shown in Figure 16 would seem to be a dangerous exposure. Is this a typical working condition, or do you work at lower energy and live scan rates? Have you measured a damage threshold?

Authors: You are correct that in Figure 16, the beam energy (6 kV) is high enough to cause damage to MOS gate oxides. In a previous paper (1) we found that low beam voltages (<3 kV) produced no detectable changes in transistor threshold or field effect mobilities even at electron fluences (10 C/cm), three orders of magnitude higher than that required by this technique. In the specific case of Figure 16, higher beam voltages were used for convenience because this driver matrix had already been found to be defective by examination at low accelerating voltage.

D. Koehler: Can you explain why twin boundaries can only be observed by the Schottky barrier charge collection method?

Authors: Schottky barrier charge collection is useful in distinguishing coherent from incoherent boundaries. P-n junction charge collection microscopy can also be used to distinguish coherent boundaries from incoherent boundaries if the boundary intersects the p-n junction. In this paper we have referred to the coherent boundaries as most likely being twin boundaries since these are low energy boundaries (i.e., are energetically probable).

J.D. Schick: How are the electrical connections to source and drain preserved while etching the gate region before SEM charge collection measurement?

Authors: In the devices shown in this paper, the gate electrode was simply a layer of aluminum over the gate oxide. Patterned photoresist allowed the etch removal of the aluminum gate electrode while preserving the source and drain electrodes.

J.D. Schick: How are electrical connections made to the specimen?

Authors: Electrical connections were made using silver paint to contact aluminum electrodes on the array side and fine electrical wires glued to the silver paint were connected to the SEM electrical feedthrough plugs. In general, we found that silver paint is troublesome and can be a source of high resistance. Wire bonding to a modified chip holder is a much better approach.

J.D. Schick: When making Schottky barrier charge collection measurements, how do you determine that the contrast is not related to local differences in electron beam absorbtion due to features in the aluminum or on the aluminum top surface?

Authors: In the case of grain boundaries, there was a clearcut correlation between the electron channeling image and the charge collection image. Moreover, switching to the secondary electron mode showed no correlation to the aluminum morphology. However, in the case of other features, such as the point images seen in Figure 11, we did not determine whether these were electrically active defects due to aluminum spiking (equivalent to a local change in doping) or topographical defects such as hillocks which decrease the effective penetration of the beam.

J.D. Schick: Do you have evidence whether the enhanced diffusion occurs along the oxide/grain boundary interface or in depth along the grain boundary in the bulk of the film? Did you make any measurements on sectioned devices?

Authors: We did not pursue this interesting point since our goal was to learn how to recrystallize polysilicon into material with no electrically active defects. Sectioning would have been informative but might have been difficult since the recrystallized films were only 300-500 nm thick.