

Thin Film Power Source Integrated With a-Si:H/a-SiGe:H Thin Film MOSFETS on Flexible Substrates

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Abstract

Flexible displays are enabled by electro-optic devices integrated with an active matrix backplane which must have its own power system. Powered thin film transistors in each display pixel must switch and power an electro-optic device. Other applications include integrated analog organic electronics, reconfigurable flexible antennas, as well as flexible explosive detection. Micro autonomous sensor systems must have the power system integrated with lightweight flexible electronics. The present paper reports the achievement of an integrated power distribution system for flexible electronics based on a PEM flexible organic polymer foil substrate (Kapton) and a-Si:H/a-SiGe:H thin film n and p MOSFETs, integrated with a thin film RuO_x/Zn/Pb power cell. Such a flexible substrate has a glass transition temperature of 320 C which will allow all standard semiconductor processes to be implemented. The limited processing temperatures introduces residual stresses and subsequent mechanical fatigue problems which must be resolved.

INTRODUCTION

The emerging field of flexible electronics is growing on many fronts and holds great promise for applications within electronic systems. The unique display needs of harsh environment, reliability, light weight and need for flexible power systems make the development of integrated flexible electronics with power systems a necessity. Flexible displays are enabled by electro-optic devices integrated with an active matrix backplane which must have its own power system. Powered thin film transistors in each display pixel must switch and power an electro-optic device. Other applications include integrated analog organic electronics, reconfigurable flexible antennas, as well as flexible explosive detection. Micro autonomous sensor systems must have the power system integrated with light weight flexible electronics.

The present paper reports the achievement of an integrated power distribution system for flexible electronics. The demonstration module is based on a PEM flexible organic polymer foil substrate (Kapton) and a-Si:H/a-SiGe:H/a-SiC thin film transistors which has been integrated via the source electrode with a thin film RuO_x/Zn/Pb power cell. Our approach is to create a hydrated ruthenium oxide/ metal galvanic redox cell. In such a system, the electrolyte is charged by redox processes occurring at the RuO₂/xH₂O electrode. We report on processing parameters for both the power source and the flexible substrate, as well as to identify processing limitations.

FABRICATION PROCEDURE

The present approach consists of fabricating the thin film transistors directly onto the kapton or thin stainless steel flexible substrate and then connecting the power input interconnects to the flexible substrate using reflow soldering in order to provide bias to the source and drain of the MOSFETs. The fabrication of the integrated structure consisted of a flexible wafer with a 320x320 pixel array and an area for test circuitry as well as two 64x64 arrays.

Figure 1 is a diagram of an individual pixel. The display allows each pixel to be addressed in the matrix by row and column drivers. The schematic diagram of an individual pixel circuit shows that is composed of a thin film transistor, a capacitor connected between the transistor's drain contact and ground, and the connection of the bottom electrode of pixel connected to the drain contact as well. Electro-optic material is then deposited on the bottom electrode, either electrophoretic or organic, and then a top transparent electrode is then deposited to complete the pixel[1-3].

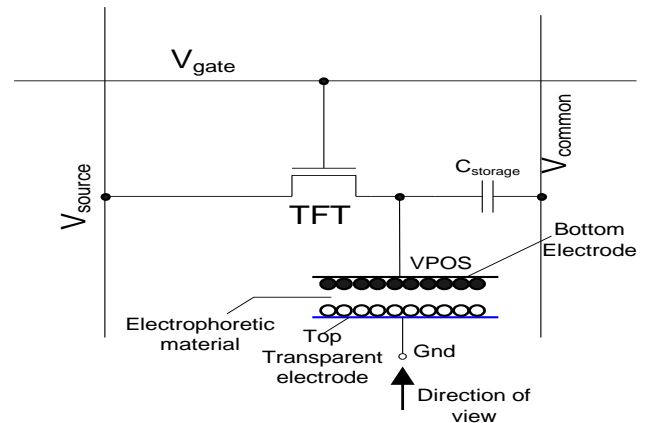


Figure 1 Schematic diagram of one pixel circuit.

The cross section of the TFT with each of the layers is shown schematically in Figure 2. The silicon nitride overglass layer is not shown, but the gate dielectric as well as the amorphous silicon and SiGe/Si active layer is shown in the figure.

RESULTS AND DISCUSSION

Electrical characteristics are measured for each test transistor fabricated on the wafer located next to the display array. Figure 3 shows the set up for measuring drain current. Note that the leakage current is the drain current below V_{gs} = 0V.

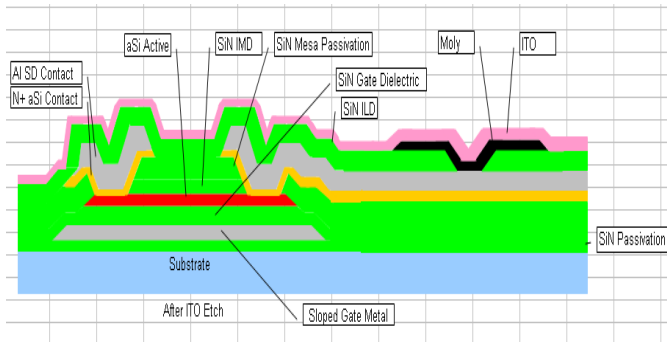


Figure 2 Cross section of the TFT.

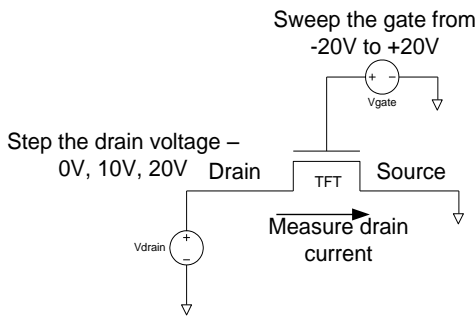


Figure 3. Schematic for measuring drain current and for I_{ds} versus V_{ds} .

Also shown in Figure 3, is the setup for measuring I_{ds} versus V_{gs} as well as the actual plots for each five volt increment (Figure 4). Drive current is measured for each transistor in the entire array.

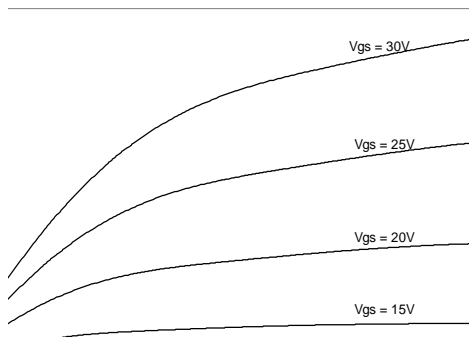


Figure 4. I_{ds} versus V_{gs} and and V_{DS} .

Signature of amorphous Silicon

Fourier Transform Infrared (FTIR) Spectroscopy was used for determining the impurity concentration of the amorphous silicon being used. This will provide a signature of the material and give insight into the bending modes and bond vibrational modes. Optical absorption was also used to characterize the optical band gap of the amorphous silicon

compounds, as well as electron spin resonance to determine the density of states. We determined that material with an optical band gap of 1.55eV was optimum in terms of minimizing transistor leakage currents. Figure 5 shows the variation of band gap with composition, as well as the variation of optical gap with hydrogen content.

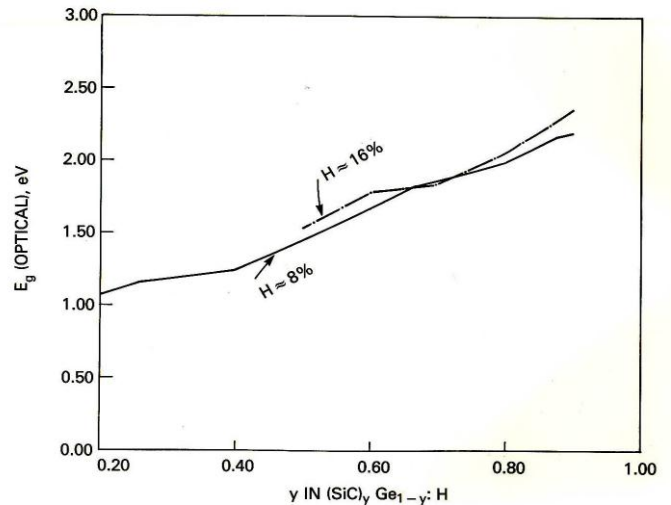


Figure 5. Shows the variation of band gap with composition.

Flexible Power Source Fabrication

Flexible batteries have been a research interest over the past decade. Electrochemical cells that can conform to a variety of electronic system packages and cells that can be embedded in flexible electronic systems are of tremendous technological importance[4]. Previous work has demonstrated that it is possible to make flexible cells with near-theoretical volumetric storage capacities. We present a flexible galvanic cell that can be optimized for volume manufacture. In addition, we describe a flexible cell whose attributes favor radio-frequency charging, as they are able to utilize low recharging voltages. Using the approach described in this paper, it is easy to create “hybrids” of redox-cells and supercapacitors. These cells are both non-toxic and environmentally friendly. The cells demonstrate a specific capacity of over 2mA h/cm^2 - among the largest reported for thin film cells. Our approach is to create a hydrated ruthenium oxide ($\text{RuO}_2 \cdot x\text{H}_2\text{O}$) /metal galvanic redox cell (a battery). In the past, $\text{RuO}_2 \cdot x\text{H}_2\text{O}$ has been used as a supercapacitor material as a result of its ability to generate high pseudo-capacitance. In such systems, the electrolyte is charged by redox processes occurring at the $\text{RuO}_2 \cdot x\text{H}_2\text{O}$ electrode. A dipole layer is formed by charge injection across the $\text{RuO}_2 \cdot x\text{H}_2\text{O}$ /electrode interface and the amount of charge transported is proportional to the change in electrode bias. The constant of proportionality is the pseudo-capacitance. This is a “Faradaic” process, whose details are the subject of many studies[5-8]. This process is distinct from that of the electrochemical double-layer cell. Here, electrode bias charge forms an image in the electrolyte and no mobile charge crosses the boundary. As the supercapacitor has demonstrated, reduction of the $\text{RuO}_2 \cdot x\text{H}_2\text{O}$ material is possible. As such, it can form a redox couple with an oxidizable metal (like a zinc anode, or, as we shall show, aluminum) to form a battery. Little work has been reported on

the use of this material system as a redox cell. This is possibly due to its relatively high internal resistance. For low power electronics, though, small amounts of current must be sourced over long periods of time. This offsets the internal dissipation of the cell. Also, as we shall show, $\text{RuO}_2 \cdot x\text{H}_2\text{O}$ redox systems initially exhibit low internal resistance, enabling large amounts of “burst” power. In any event, it is clear that hybrid combinations of $\text{RuO}_2 \cdot x\text{H}_2\text{O}$ /metal

and $\text{RuO}_2 \cdot x\text{H}_2\text{O}$ // $\text{RuO}_2 \cdot x\text{H}_2\text{O}$ electrode combinations can be made in which the first combination serves as a battery and the second as a supercapacitor, as described above. There are a number of other potential advantages of the $\text{RuO}_2 \cdot x\text{H}_2\text{O}$ cell. Hydrated

ruthenium oxide exists in a multiplicity of oxidation states and, as the $\text{RuO}_2 \cdot x\text{H}_2\text{O}$ /metal cell discharges, all of these oxidation states can be exercised, leading to a “graceful” rather than a discontinuous drop in source potential. In the past, such a graceful discharge was viewed as undesirable for a battery. With the advent of ultralow-power, low-volume integrated circuit voltage regulators, this is no longer the case. Hydrated ruthenium oxide itself is a “nanopowder” with a surface area that may approach tens of square meters per gram (like nano-powder activated carbon) to enable the reaction to proceed. When compounded with activated carbon (AC), the layer resistance drops, and the weight percentage of relatively expensive ruthenium is reduced to less than 10%. The resulting paste is patternable using standard silk-screening techniques. Thin separating papers can be interposed between the $\text{RuO}_2 \cdot x\text{H}_2\text{O}$ and the counter-electrode. As the counter-electrode, we have studied the use of foils of zinc and aluminum, and of powders of zinc for surface area enhancement. All of these approaches yield viable electrochemical cells. We implemented the cells with an electrolyte composed of a weak acid and ethylene glycol that is close to neutral pH to prevent rapid dissolution of the electrode materials or

package sealing materials while favoring the needed redox reactions. In fact, our working pH is 5. This enables the reaction chemistry to proceed as close to equilibrium as possible to allow electrically driven reversibility (re-charging). The system of materials and the packaging approach used are targeted to yield a cell with small weight, small volume and high flexibility. Integration with thin film transistors on a flexible polymer substrate has been achieved by attaching the battery via Van der Waals forces onto the common substrate. Displayed in figure 2 we see the physical cross-section of an amorphous silicon thin film transistor on a flexible substrate. These transistors when powered with the flexible battery allowed us to obtain the current –voltage characteristics shown in Figure 4.

Perhaps the most interesting aspect of the $\text{RuO}_2 \cdot x\text{H}_2\text{O}$ cells is their short-term discharge capacity. The sourced current remains high (higher than 10 mA for the 16 cm² cell) for over ten minutes of operation. On average, this leads to a specific capacity of about 0.2 mA-h/cm² over this ten minute period. We have also examined the long-discharge behavior of the battery through a large load

(as would be typical of operation in an ultra-low power system). Note that the current remains higher than 0.4 μA for over 110 days. The integration out to 110 days yields a 2.32 mA-h/cm² specific storage capacity. When extrapolated to 150 days, this yields 2.43 mW-h/cm². Now let us turn to the demonstrated applications of our battery. The $\text{RuO}_2 \cdot x\text{H}_2\text{O}$

cells are perfectly capable of performing routine electronic system power sourcing tasks, such as the flexible cell lighting an LED. We have also addressed somewhat more challenging source requirements such as power for integrated circuits. Perfect IV characteristics for enhancement mode transistors have been obtained, as well as for transistors configured as an inverter chain.

4. CONCLUSIONS

We have demonstrated flexible electronics powered by an electrochemical cell that can conform to a variety of shapes and package configurations. Flexible redox-cells integrated with n MOSFETs and inverter chains have been demonstrated. A composite structure made of cells of this battery type was able to source over 30mA for over 4.5 minutes into the supply rails of amorphous silicon based thin film transistor inverters.

5. REFERENCES

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