Information Displays in the Twenty-First Century

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The information display industry this century has to improve our life without increasing energy consumption. Suftla technology together with high-performance silicon thin film transistors (TFTs) and ink-jet technology for forming metal-wiring and organic TFTs will play leading roles for achieving this requirement. In this paper these technologies are reviewed and the concept of the information displays in near future is discussed.

1. Introduction

Our world is facing the prospect of deepening social crises due to the looming destruction brought on by the disastrous effects of global warming, wars that may arise between nations vying for energy resources, and terrorism arising in response to war. Environmental and energy problems are, thus, having an increasingly profound impact on human social activity. To solve these problems, we need to reduce per-capita energy consumption to roughly one-tenth its current level or boost energy efficiency tenfold. We also must keep carbon dioxide emission to at least the current level. In the 21st century industry must advance while contributing to human happiness and solving these environmental and energy problems. In other words, we can grow the economy while also reducing energy consumption and carbon dioxide emissions.

It is from this perspective that we have developed Suftla technology together with high-performance silicon TFTs and ink-jet technology for organic TFTs and metal-wiring. In this paper these technologies are reviewed in detail and the concepts of information displays in the near future are discussed, in the hopes of realizing an environment-friendly sustainable world.

2. Suftla Technology

Almost all large-scale-integration (LSI) devices are now produced on silicon wafers. The wafer must be single-crystalline and free of defects over the entire wafer surface. These requirements for the silicon wafer make the fabrication of LSI devices problematic in terms of energy and cost. Although the production of LSI devices consumes a great deal of energy and effort, only a very small percentage of the silicon wafer is utilized as the active transistor area in the actual devices. The rest of the silicon wafer is simply used as an electrically inactive supporting body. The present semiconductor technology is thus built on an environmentally inefficient concept. Suftla technology together with high-performance silicon TFTs can solve the aforesaid dilemma, because Suftla does not depend on single-crystal silicon wafers, and high-performance TFTs can compete with LSI devices.

Suftla is a technology that is used to transfer TFT circuits from an original glass substrate to another material, such as a plastic sheet [1-2],

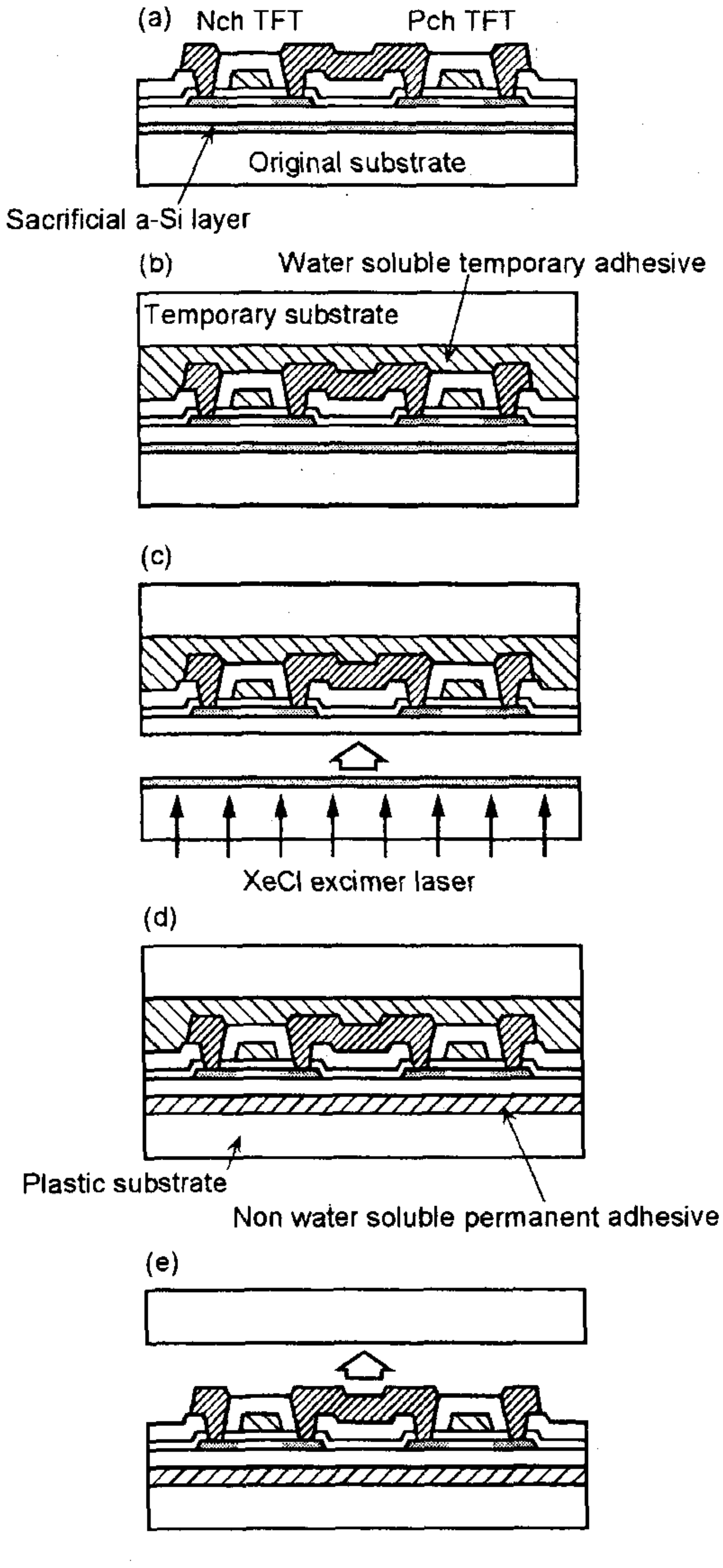


Fig. 1 Suftla process

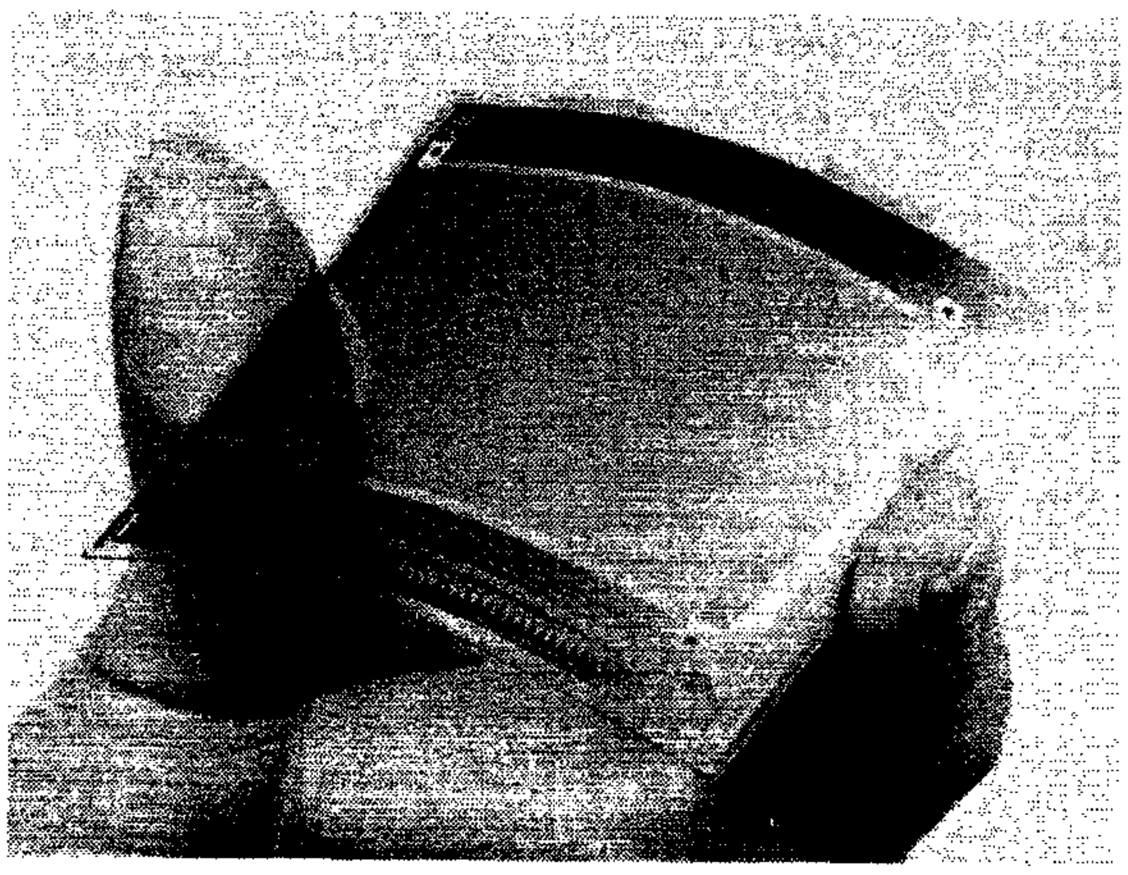


Fig. 2 TFT AM-OLED on Plastic Sheet

thereby lifting the restriction that LSI devices must be made on silicon wafers. Figure 1 schematically illustrates the Suftla process sequence. Before fabricating TFT circuits on an original glass substrate, a sacrificial amorphous silicon (a-Si) layer is formed on the substrate. This follows the standard fabrication of polycrystalline silicon (polysilicon) TFTs through a low-temperature process (Fig. 1a). After completion of polysilicon TFTs on the original glass substrate, a temporary glass substrate is glued onto the TFT surface using a temporary water-soluble adhesive (Fig. 1b). Xenon chlorine (XeCl) excimer laser light (λ = 308 nm) is then irradiated onto the sacrificial a-Si layer from the back side of the original glass substrate. This process weakens the sticking force at the interface of the sacrificial a-Si layer, resulting in an easy separation of the TFT devices from the original glass substrate (Fig. 1c). After the separation, the back side of the TFT devices is glued onto a target substrate, such as a plastic sheet, using the permanent adhesive, which is not water-soluble (Fig. 1d). Finally the temporary water-soluble adhesive is dissolved into water to remove the temporary substrate (Fig. 1e). The TFT devices are thus successfully transferred onto the plastic sheet.

Suftla technology enables TFT circuits to be easily and completely transferred. Neither degradation of transistor properties nor mechanical damage of TFT circuits due to the Suftla transfer process has been observed. The transfer yield is approaching 100%. Figure 2 shows a Suftla example of a TFT active-matrix organic light-emitting diode (AM-OLED) display that has been transferred onto a plastic sheet. TFT circuits on the AM-OLED display operate correctly and therefore the display shows beautiful images on the plastic sheet. The Suftla technology enables us to make TFT-LSI circuits on some materials other than silicon wafers.

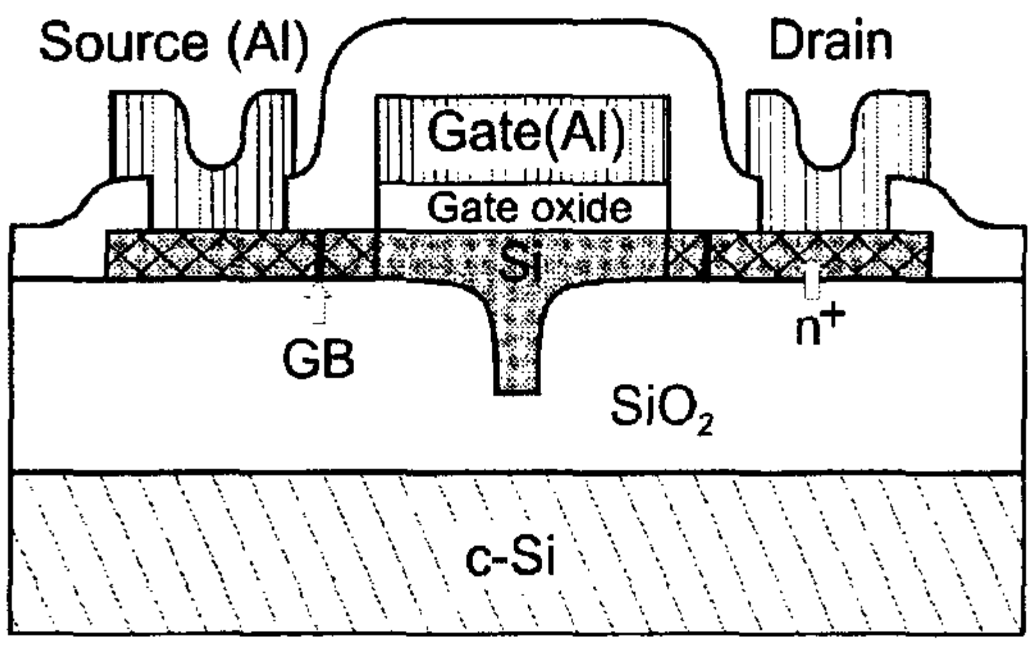


Fig. 3 Micro-Czochralski TFT

3. High-performance Silicon TFTs

Suftla is a great technology, but in order to win a substantial share of the semiconductor market, the transistor properties of TFTs must first competitive with those of metal oxide semiconductor field effect transistor made on silicon wafers.

The most serious problem associated with polysilicon TFTs comes from the polycrystalline nature of the semiconductor film [3]. The scaling rule of TFT devices reduces transistor dimensions to less than the typical crystalline grain size. Hence, the transistor properties depend strongly on whether the transistor contains crystalline grain-boundaries. The idea of single-grain silicon thin film transistors (SG-Si TFTs) overcomes this problem and eliminates the random aspect of the microstructure of conventional polysilicon films. In SG-Si TFTs, crystalline grains are artificially produced at the exact places where the active areas of the transistor are to be formed.

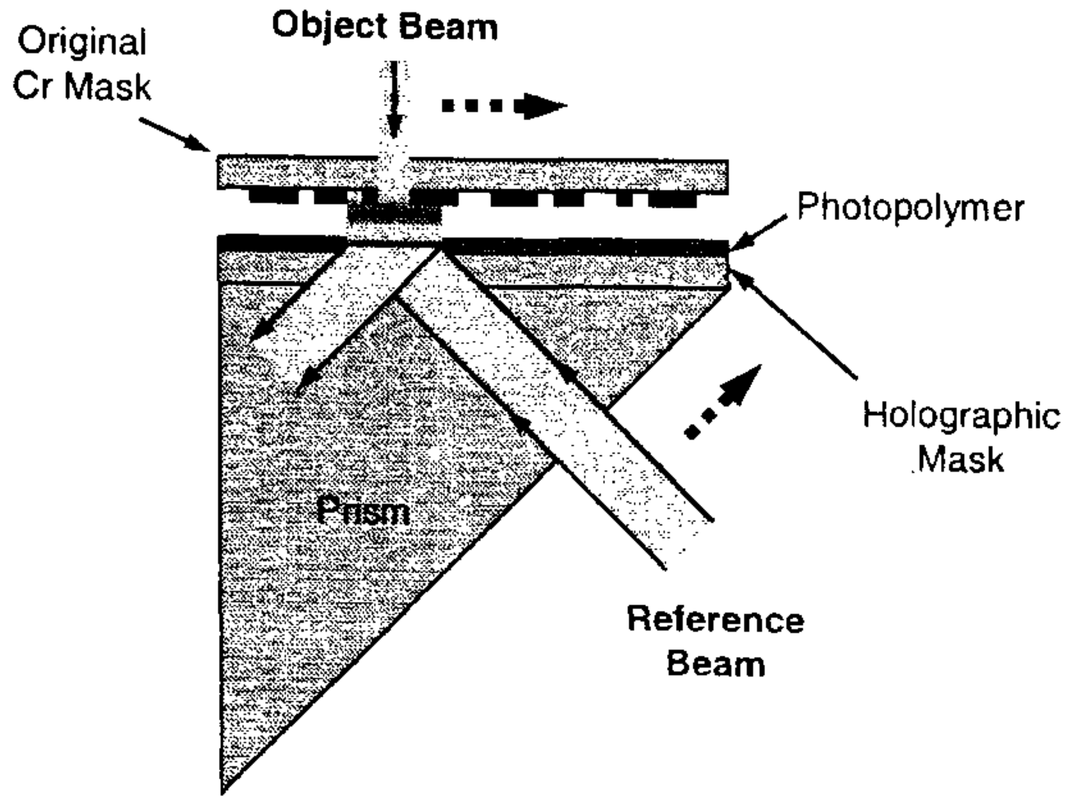
One conceptually straightforward method to realize the hope of making SG-Si TFTs is called "Micro-Czochralski technology" [4]. This technology controls the positions of crystalline grains, utilizing the excimer laser annealing (ELA) of an a-Si film and local melting process of the silicon film. Figure 3 is an illustration of this technology, showing that a narrow hole is formed at the transistor position and that the hole is filled with a-Si film. During the ELA process the upper part of the silicon film is completely melted. In contrast, the silicon film located near the bottom of the hole remains in a solid state and acts as crystalline nucleation seeds. Because of the deep narrow hole, only one crystallite, the one that has the fastest growth rate along the vertical direction, is naturally selected during the vertical growth to form a large crystalline grain around the hole. SG-Si TFTs made on the location-controlled crystalline grains possess high mobility values of approximately 500 $cm^2 V^{-1} s^{-1}$.

The scaling rule is obeyed in the TFT industry as well as in the LSI industry. The relationship between the optical resolution R and the depth of focus *DOF* of the photolithography system is expressed by the Rayleigh equation

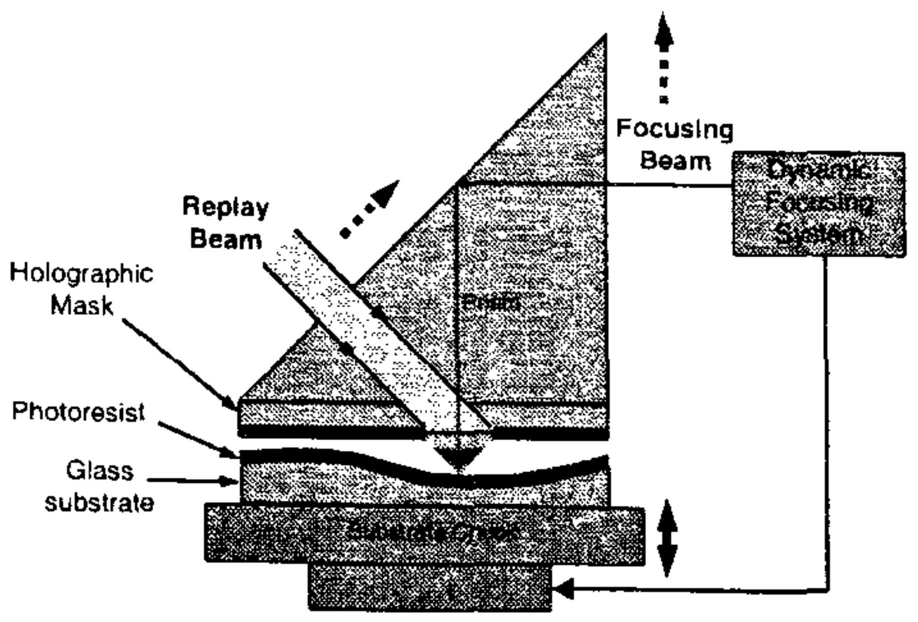
$$DOF = k \cdot \frac{R^2}{\lambda} \quad ,$$

where λ is the wavelength and k is a constant ($k \approx 0.6$). The higher resolution (smaller value of R) makes the *DOF* shorter. When a resolution of 3 µm is required with *g*-line (λ = 436 nm) light, the *DOF* is 12 µm. However, when we need a resolution of 1 µm with *i*-line (λ = 365 nm) light, the *DOF* becomes as short as 1.6 µm. A standard glass substrate has a thickness variation of approximately 10 µm. This had prevented the size of TFTs from being reduced to below several microns. A newly developed holographic lithography system improves this situation and realizes sub-micron TFTs on a standard glass substrate [5].

The holographic lithography system needs two stages to print sub-micron patterns on a glass substrate. The first stage is the hologram recording of original patterns onto a holographic mask (Fig. 4a). An object beam passing through the original patterns interferes with a reference beam on the holographic mask to be transformed to the holographic patterns. The second stage is the hologram replaying of the holographic patterns onto a glass substrate (Fig. 4b). The lithography system keeps the distance between the holographic mask and the glass substrate constant during the hologram replaying. Therefore the glass substrate is always in focus and sub-micron TFTs, for example with a gate-length of 0.5 µm, are easily fabricated on a large glass substrate. Transistor properties of the sub-micron TFT are confirmed to be good.



(a) Hologram Recording



(b) Hologram Peplay

Fig. 4 Holographic Lithography

The combination of Suftla technology and high-performance SG-Si TFTs with sub-micron design rules will definitely replace some parts of the current LSI industry, because TFT properties are comparable with bulk LSI properties and we do not need single crystal silicon wafers for TFT fabrication. In the near future information displays will be made on plastic sheets and will include a TFT central processing unit, TFT memories and so on.

4. Ink-jet Printing

LSI and TFT devices are currently fabricated by a repetitive cycle of deposition, photolithography and etching. Both the deposition and etching process need a vacuum and, thus, consume vast quantities of energy. After the etching process less than a few percentage of the deposited film is left to be utilized in an actual device. The rest of the film is etched away. Also, one hundred percent of photo-resist is finally disposed of. The present fabrication process for LSI and TFT devices is a total waste of energy; it should be modified.

The solution-processed formation, which does not need expensive vacuum equipment, can reduce the energy consumption and make it possible to apply low-cost and high-efficiency patterning techniques such as micro-molding, micro-contact printing, screen printing and ink-jet printing (IJP). IJP has advantages over the other techniques with respect to adaptable, non-contact and large-area patterning, and thus has emerged as an attractive patterning technique for color filters for liquid crystal display [6] and conjugated polymers in light-emitting diode displays [7].

IJP technology has to satisfy the three basic requirements of 1) preparing functional liquid suitable for the ink-jet process; 2) directly printing the functional liquid with a high accuracy; and 3) transforming the liquid into the functional solid without degrading its functionality. An important example of IJP technology is given in a metal-wiring formation on a glass [8]. Silver nano-particles dispersed into organic solvent are employed as a special ink for ink-jet printing. The special ink has to possess a viscosity of less than 10 mPa s and a surface tension of 20 - 50 mN m^{-1}. Moreover, the organic solvent must have a low vapor pressure in order to inhibit fast drying and avoid clogging up the ink-jet nozzles. The ink-jet print head used in this work is a piezoelectric type and ejects ink droplets of 2 pl in volume, i.e. 15 μm in diameter, at a rate of 32,000 shots per second per nozzle. Controlling the oleo-phobic and oleo-philic nature of the glass surface enables us to draw fine metal lines. Silver lines thus ink-jet printed have a width of 30 μm and thickness of 0.5 μm, with a resistivity of 2 μΩ cm.

Another important example of IJP technology is seen in the fabrication of organic TFTs [9], in which a conductive polymer, PEDOT (poly-ethylenedioxythiophene, Baytron P, Bayer AG), serves as the metal layer; an insulating polymer, PVP (poly-vinylphenol), serves as the gate-insulator; and a conjugated polymer, F8T2 (fluorene-bithiophene copolymer), serve as the semiconductor layer.

IJP technology had never been applied to organic transistors until the end of the last century, because its resolution was limited to 20 to 50 μm by statistical variations of the flight direction of droplets and their spreading on the substrate. This is not sufficient for defining source-drain electrodes of practical TFTs without accidental electrical shorts. This problem has been overcome by confining the spreading of water-based PEDOT ink droplets on a wetting (hydrophilic) surface with a dewetting (hydorophobic) pattern of narrow polyimide (PI) stripes that define the critical device dimensions. When droplets of water-based PEDOT solution are deposited onto the hydrophilic region along the hydrophobic PI stripe with a certain distance from the edge, the solution flows up to the edge of the PI stripe, but still confined in the hydrophilic region (Fig. 5a). The atomic force microscope (AFM) image of Fig. 5b shows that PEDOT is successfully deposited up to the very edge of the PI stripe, defining the source, drain and channel-formation areas. The organic TFTs thus fabricated exhibit fairly good transistor properties, such as a high on-off switching ratio of more than 10^5. During the organic TFT fabrication process one photolithographic step is used to form the PI stripe.

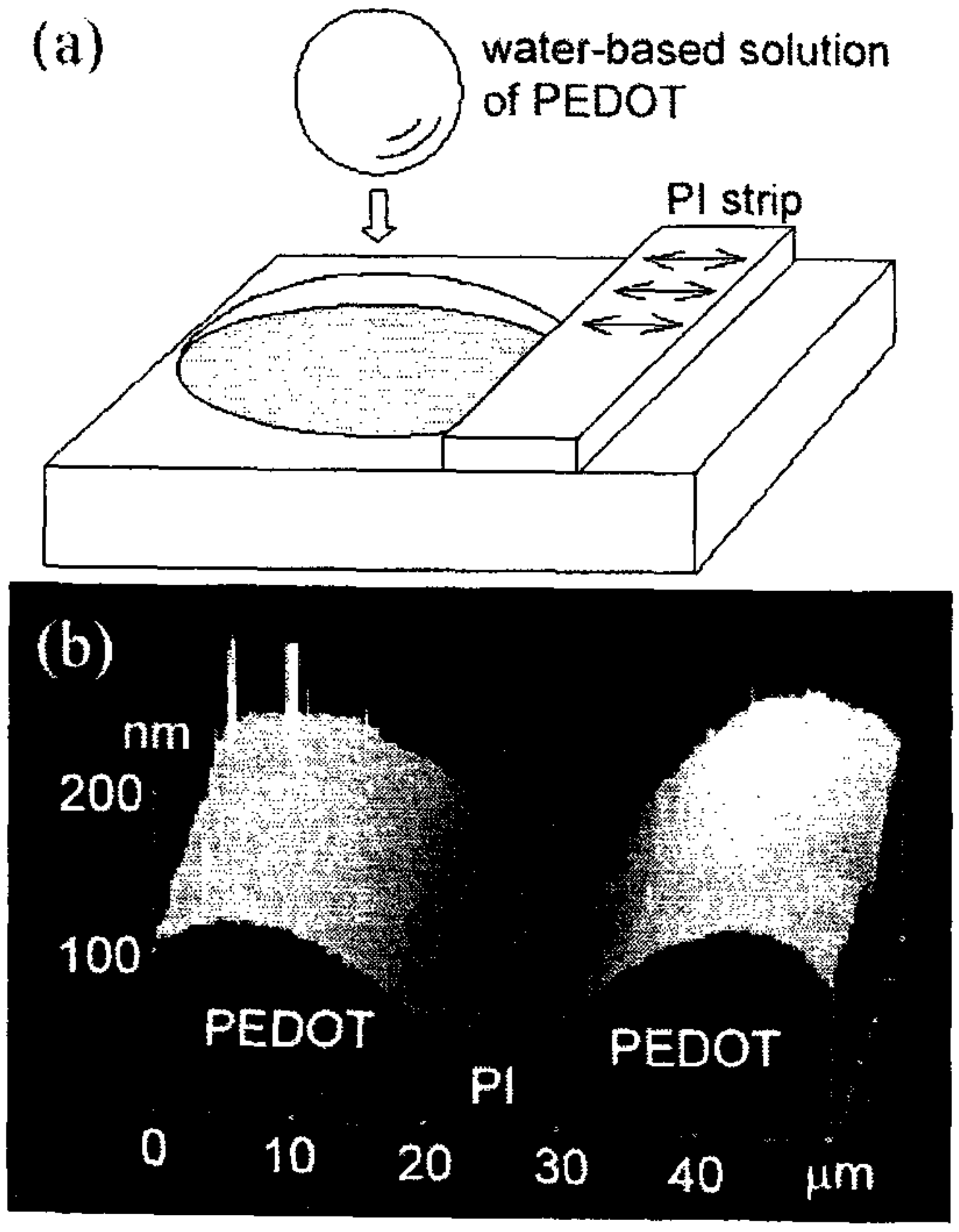


Fig. 5 Ink-jet deposition of PEDOT

5. Future Displays

Displays will be made on flexible materials in the future. Combination of Suftla technology and sub-micron SG-Si TFTs will produce high-quality, highly sophisticated displays. In contrast, IJP technology for forming metal-wiring and organic TFTs will realize cheap e-paper [10]. E-paper will use an active-matrix electro-phoretic display (EPD) in which micro-encapsulated electro-phoretic material is integrated with an ink-jet printed polymeric active-matrix TFT backplane. In the current display data lines and pixel electrodes were processed with a standard vacuum process and photolithography, though they will soon be made with IJP metal-wiring technology.

6. Conclusion

It is our duty to develop eco-friendly processes and products. Suftla technology together with sub-micron SG-Si TFTs will greatly reduce the energy consumed for fabricating LSI circuits and highly-sophisticated displays. Likewise, IJP technology for forming metal-wiring and organic TFTs will someday realize e-paper, reducing paper consumption, protecting forests, and keeping our world green.

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