

Current Status of Flexible Microelectronics; TFT Asynchronous Microprocessor on Plastic

Mitsutoshi MIYASAKA, Nobuo KARAKI ¹⁾ and Tatsuya SHIMODA ²⁾

Seiko Epson Corporation

Flexible Microelectronics Project

1) Technology Platform Research Center

2) Corporate R&D

Tel:81-266-61-1211, Fax:81-266-61-0674, E-mail: miyasaka.mitsutoshi@exc.epson.co.jp

Thin film transistors (TFTs) are field-effect transistors that can be used to create large-scale integrated (LSI) circuits. The combination of Suftla technology and high-performance TFTs has the potential to foster the rise of a new flexible microelectronics industry. This paper reviews the history of Suftla technology and discusses the current status of flexible microelectronics, a TFT asynchronous microprocessor. We are sure that there is a best fit between the advantages of the asynchronous circuit and the electrical properties TFTs possess, because the asynchronous circuit overcomes the deviation of transistor characteristics, is free from the signal delay problem and does not generate a large amount of heat. TFT technology should not be confined to the display industry; its use should be expanded into the semiconductor industry. We are on the verge of a new era of flexible microelectronics.

1. Introduction

Polycrystalline silicon thin film transistors (polysilicon TFTs) are inching toward metal oxide semiconductor field effect transistors (MOSFETs) formed on a single-crystal silicon wafer. Early on, when polysilicon TFT technology first became feasible, TFTs possessed a mobility value of less than $10 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and the TFT circuits were only able to transfer a few triggering pulses [1]. Today, the mobility value of polysilicon TFT is as large as $100 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and the TFT circuits can process the analogue signals [2]. It is widely believed that within a decade polysilicon TFTs will become the single-crystal devices and that TFT circuits will be used as large-scale integrated (LSI) circuits.

Looking back over the history of semiconductors, semiconductor devices have continued their remarkable advancement in

accordance with the scaling rule for nearly half a century. Though we hope for further advancement, the technology seems to be reaching its limits. Theoretically the silicon band-gap limits the lowest voltage to approximately 0.5 V. In addition, there appear to be serious technical difficulties in achieving finer patterning and thinner gate-dielectric. From a business perspective, the advantages gained by further scaling are spoiled by the high research, development and fabrication costs. Taking these facts into account, we propose improving semiconductor devices this century by eradicating the notion that LSI devices must be made on silicon wafers.

Suftla (surface-free technology by laser annealing / ablation) is a superb technology that enables TFT circuits to be transferred to a plastic sheet [3]. The combination of Suftla and high-performance polysilicon TFT technologies will foster a new flexible microelectronics industry, which will realize TFT LSI circuits on a plastic sheet.

This paper reviews the history of Suftla technology and discusses the current status of flexible microelectronics, focusing especially on the highly functional TFT circuit. The world's first practical TFT microprocessor is presented as an example of TFT LSI circuits.

2. Suftla Technology

Suftla is a technology that transfers TFT circuits from an original glass substrate to another material [3], such as a plastic sheet, thereby lifting the restriction that LSI devices must be made on silicon wafers.

Before fabricating TFT circuits on an original glass substrate, a sacrificial amorphous silicon (a-Si) layer is formed on the substrate (Fig. 1a). This follows the standard fabrication of polysilicon TFTs through a low-temperature process. After completion of polysilicon TFTs on the original glass substrate, a

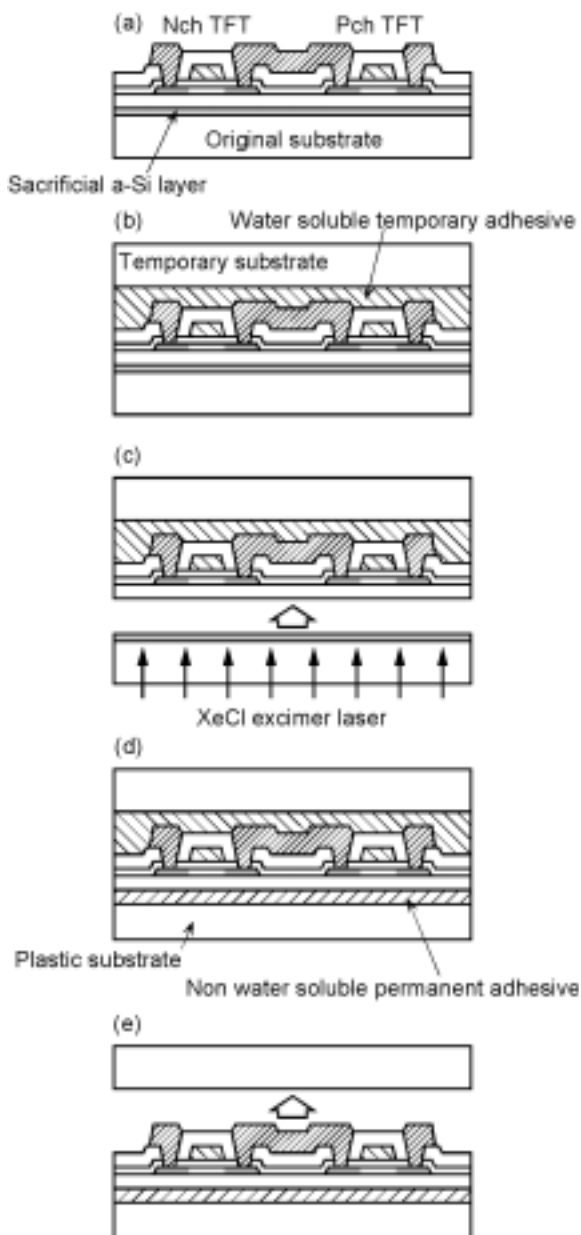


Fig. 1 Suflta process

temporary glass substrate is glued onto the TFT surface using a temporary water-soluble adhesive (Fig. 1b). Xenon chlorine (XeCl) excimer laser light ($\lambda = 308$ nm) is then irradiated onto the sacrificial a-Si layer from the back side of the original glass substrate (Fig. 1c). This process weakens the sticking force at the interface of the sacrificial a-Si layer, resulting in the easy separation of the TFT devices from the original glass substrate. After separation, the back side

of the TFT devices is glued onto a target substrate, such as a plastic sheet, using a permanent adhesive that is not water-soluble (Fig. 1d). Finally, the temporary water-soluble adhesive is dissolved in water so that the TFT devices can be removed from the temporary substrate (Fig. 1e). The TFT devices are thus transferred onto the plastic sheet.

Suflta technology has advanced considerably. In the year 2000, 107-stage static shift-register circuits operated correctly on polyethersulphone (PES) film [4]. The operation voltage was 7.0 V and the maximum clock frequency was 2 MHz. These were the world's first TFT large-scale circuits that were transferred to and worked correctly on a plastic film. The next year, 2001, we fabricated polysilicon TFT active-matrix liquid crystal displays (AMLCDs) on a plastic film [5]. The first flexible microelectronics device was a 0.7 inch in diagonal monochromatic AMLCD. Although we had many defects on the display and the contrast ratio was not good, the flexible device displayed images. Since the peripheral driver circuits were integrated with TFTs on the plastic AMLCD, the plastic device, which possesses 101,864 pixels, displayed with only 60 external connections. Fewer external connections are highly desirable for flexible devices, because it is not easy to achieve stable electric connections on a flexible sheet.

Monochromatic and color organic light-emitting diode (OLED) flexible displays were successfully fabricated in 2002 [6] and 2003 [7], respectively. The display was 2.1 inches in diagonal and included 200×150 pixels. Each pixel was made up of 9 sub-pixels, 3 for the primary color (red, green and blue) and 3 for 2-bit area ratio gray-scale. Combining the 2-bit area ratio gray-scale and the other 2-bit time ratio gray-scale, we saw 16 gray-scale per color. TFT digital circuits used therein included static shift-register, buffer and latch circuits. These circuits operated well on a plastic film, enabling the digital line-at-a-time driving method to show us beautiful moving pictures on the plastic display. The flexible display weighed 3.2 g, compared to about 10 g for a glass-based display, thus demonstrating the potential of flexible microelectronics to significantly reduce device weight.

Last year in the IMID 2004 we officially declared a new era of flexible microelectronics opened, presenting the world's first plastic fingerprint sensor (FPS) [8] and active-matrix electrophoretic display (AMEPD) [9]. The plastic FPS contained both digital and analog circuits. The digital circuits

operated correctly on plastic at voltage as low as $V_{dd} = 1.5$ V, demonstrating the ability of TFT circuits on plastic to compete with crystalline silicon circuits. The plastic FPS can be embedded in a smart card to secure the card against financial or information attacks.

Although we had succeeded in developing flexible AMLCD and OLED devices, there were technical difficulties in making these devices practical for business. Producing flexible backplanes using Suflta technology is not a serious problem, but producing flexible liquid crystal or OLED display modules is highly problematic. In order to complete these display modules, we have to clear the hurdles in the complicated fabrication process once the flexible backplanes are obtained. In contrast to these display modules, the AMEPD module can be easily fabricated. A micro-encapsulated electrophoretic paste is simply coated on thin plastic film to serve as a frontplane. Laminating the frontplane onto our flexible backplane results in a flexible AMEPD device. This simple fabrication process inspired confidence in opening the flexible microelectronics era with AMEPD. The flexible AMEPD device will be used as a key device in electric paper (e-paper) in near future.

To realize our ambition of creating a new flexible microelectronics industry, we need central processing units (CPUs). This year, 2005, we developed the world's first flexible 8-bit asynchronous microprocessor [10]. The combination of Suflta, high-performance TFT and asynchronous circuit design technologies has made it possible for us to create flexible TFT CPUs that stably processes data on a plastic sheet (Fig. 2). The TFT microprocessor will be of critical importance as demand in the flexible microelectronics industry grows.

3. Requirements of TFT LSI

TFT LSI circuits on plastic have to satisfy the following four requirements.

First, the circuits have to overcome the deviations of TFT characteristics. Unfortunately TFT devices possess larger deviations in electrical properties than do single-crystal silicon devices. This problem becomes especially serious when TFT device dimension is on the same order as crystalline grain size, namely channel length of less than $2 \mu\text{m}$ [11].

Second, the circuits should solve the problem of signal delay on long wires. Since major applications of the TFT device are in large-area electronics such as displays, very long wires may be used in the TFT LSI circuits.

Third, the circuits should not generate a large amount of heat. During circuit operation TFT devices can generate enough heat to degrade TFT performance (self-heating degradation of TFT) [12]. The temperature of the TFT devices can exceed 300°C , which is high enough not only to degrade the devices themselves but also to melt and deform the plastic materials used in a flexible device. The low thermal conductivity of plastic material prevents the efficient dissipation of heat. Cool operation of TFT circuits is, therefore, especially important in flexible devices.

Fourth, the energy consumption of the circuits must be low, because many flexible electronic devices will be used in portable products with a small battery.

The asynchronous circuits we developed meet all these requirements.

4. Handshake Asynchronous Circuit

Nearly all the conventional LSI systems are classified as synchronous circuits, in which a global clock, regular tick, is supplied to every circuit block

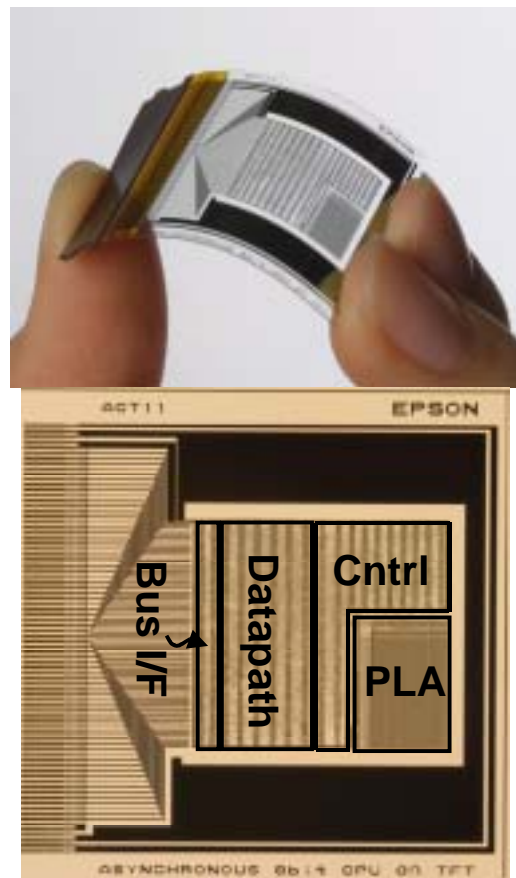


Fig. 2 TFT asynchronous microprocessor

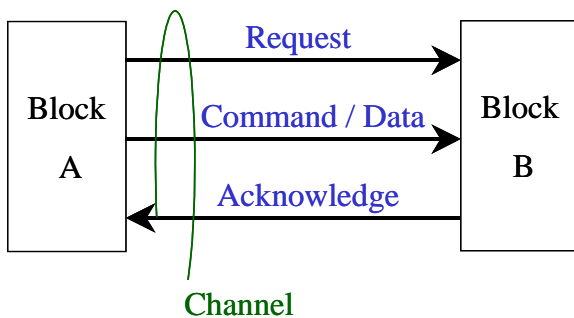


Fig. 3 Handshake communication

of the system and tells it when to act. In contrast, asynchronous circuits are clockless integrated circuits. They neither need the regular tick nor, therefore, have the global clock. Each circuit block in the asynchronous circuit is activated only when needed. The circuit blocks themselves determine when to act and communicate with each other.

Our asynchronous circuits utilize a communicating sequential process (CSP). The CSP method allows us to describe systems as a number of components, which correspond to circuit blocks in our asynchronous system, and which operate independently and communicate with each other solely over well-defined ports and channels. A circuit block handshakes with the counter circuit block when they communicate with each other (handshake technology). The handshake technology exchanges a request, a command (data) and an acknowledge between circuit blocks. An example is a data transfer (Fig. 3). A handshake starts with a request that is sent from a sender, Block A in Fig. 3, to a receiver, Block B in Fig. 3. When the data is completely transferred to the receiver and the receiver stores it, the receiver sends back an acknowledge to the sender, ending the handshake. The handshake technology enables us to design LSI circuits without the global clock and plays a central role in communications between circuit blocks in our TFT asynchronous microprocessors.

5. TFT Asynchronous Microprocessor

The asynchronous circuit with the handshake technology (handshake asynchronous circuit) offers numerous advantages. First, the circuit can work correctly over the wide range of transistor deviations. In the conventional synchronous circuit all the circuit blocks have to work synchronously with the global clock. If a transistor in a circuit block has a poor on-current value due to a large threshold value, for

example, and therefore the circuit block does not synchronize the global clock, the synchronous circuit does not work correctly. In contrast, in the handshake asynchronous circuit, since there is no global clock and since each circuit block waits until the action of the counter circuit block ends, all the communications are completed independently from the poor on-current value of a bad TFT. In other words, each circuit block in the handshake asynchronous circuits works at the

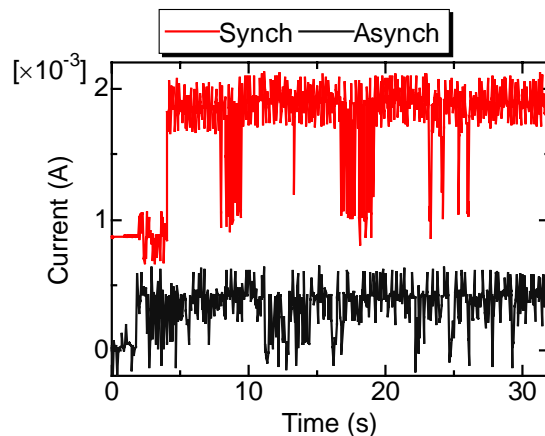


Fig. 4 Current consumption in TFT synchronous and asynchronous microprocessors

speed determined by the component TFTs (self-timed block). Accordingly, even if a circuit block includes a bad TFT, the circuit block can communicate with other circuit blocks. In fact, we have confirmed that our TFT asynchronous microprocessors work correctly in much wider voltage and frequency ranges than do TFT synchronous microprocessors. This basic nature of the handshake asynchronous circuits, self-timed blocks, gives us the second advantage that the circuit overcomes the signal delay problem. Signal delay on a long wire does not cause a malfunction in the circuit, because the handshake communication always finishes with an acknowledge.

The third advantage of the handshake asynchronous circuits is their low power consumption. Low power consumption leads to a fourth advantage: these circuits are free from heat-related problems. The TFTs do not suffer self-heating degradation, and the plastic material used in a flexible device does not melt or deform. In the conventional synchronous circuits the global clock has to permeate every circuit block of the system. Nearly the entire surface of the system is

covered with metal wires that distribute the clock signal. Each of these wires has its own parasitic capacitance, which has to be charged and discharged every time the clock ticks. Distributing the global clock to all of the circuit blocks is a very energy-consuming process. Even though some circuit blocks did not work and therefore did not need the clock signal, the global clock would always be supplied to all the circuit blocks in the conventional synchronous circuit. The synchronous circuit is, thus, essentially built on an energy-consuming concept.

In contrast to the synchronous circuit, the handshake asynchronous circuit is built on a energy-saving concept. Handshake asynchronous circuits eliminate the energy-consuming global clock. In addition, the energy is consumed only where needed. Normally we do not use all the circuit blocks of a microprocessor at the same time. Among them only a few circuit blocks work simultaneously. In the handshake asynchronous circuit only the blocks that need to work are working; the other circuit blocks are left idle without consuming energy. A direct comparison between synchronous and asynchronous TFT microprocessors definitively confirmed this. Figure 4 compares the electric current consumed in

the synchronous TFT microprocessor (red line in Fig. 4) with that consumed in the asynchronous TFT microprocessor (black line in Fig. 4). Both microprocessors execute the same instructions under the same operation conditions, namely 4 V and 250 kHz. Since our asynchronous microprocessor possesses a synchronous bus interface for perfect compatibility with a standard synchronous microprocessor, a direct comparison can be made. Although the current consumed in the asynchronous microprocessor includes both the dynamic current consumed in the asynchronous core and the clocking current consumed in the synchronous bus interface, the energy consumption in the asynchronous microprocessor is roughly 73% lower than in synchronous microprocessor. If we remove the synchronous bus interface, actual energy consumption is further reduced. The handshake asynchronous microprocessor considerably reduces energy consumption and operates at very cool temperature.

Handshake asynchronous circuits thus meet all four requirements posed by TFT LSIs on plastic.

6. Flexible Microprocessor Specifications

The 8-bit asynchronous microprocessor formed on plastic (Fig. 2) is composed of 32,000 polysilicon TFTs. The device dimensions are a 4- μm gate length and a 40-nm oxide thickness. A standard low-temperature process was used to fabricate the polysilicon TFTs; silicon films were crystallized with excimer laser light, a gate dielectric was deposited in a PECVD using tetra-ethoxy-silane, and donor and acceptor ions were activated at 400°C. Typical mobility values of NMOS and PMOS TFTs are 90 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ and 45 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$, respectively. Threshold voltage values are around $\pm 1.5 \text{ V}$ both for NMOS and PMOS TFTs. The asynchronous microprocessors correctly operate in the voltage range of 3.5 V to 7 V and in the frequency range of 30 kHz to 500 kHz. The specifications are shown in Table 1 in more detail.

The core architecture (Fig. 5) is designed so as to take maximum advantage of the handshake asynchronous microprocessor. Each circuit block works only when needed, to save energy. Output from the instruction decoder is fed to the sequencer and filter to control units such as the arithmetic unit, transfer unit and buses. The sequencer generates the sequence signals, which determine the order of operations. The filter selects units to be activated, using the output from the instruction decoder and the sequence signals. While these circuit blocks are

Technology	LTPS TFT CMOS 2 metal layers Transistor size (Typical L/W) 4 μm / 12 μm (NMOS) 4 μm / 36 μm (PMOS)
Elements	32,000 transistors
CPU Architecture	608 instructions including multiplication and division. 16 MByte addressing space. Bus release for bus masters outside 4 interrupt sources. Synchronous bus interface. Data-path: Bundle data, Single rail.
Voltage	3.5 V – 7V
Clock	30 kHz – 500 kHz
Dimensions (Core)	27.0 mm \times 24.0 mm \times 0.2 mm (12.5 mm \times 12.5 mm \times 0.2 mm)
Weight	140 mg (+100 mg FPC)
I/O Pins	80 pins

Table 1 Specifications of the TFT asynchronous microprocessor

working, all other circuit blocks are left idle to save energy. Also, an arithmetic logic unit (ALU) is divided into independent register, arithmetic, logic, shift / rotate, and transfer units. This architecture reduces energy consumption, because the units that need not work are lying idle. For example, if the ALU included shift and rotate functions, energy would be unnecessarily consumed by the adder during simple logic operations. In contrast, in our architecture the arithmetic unit does not work unless it is selected and activated.

The master unit communicates with the other units to proceed according to the sequential process of instruction fetch, decode, execute and write back. Complicated instructions, such as multiplication, are divided into the iterative sequence of microinstructions and then stored in a programmable logic array formed in the instruction decoder.

As described above, although our polysilicon TFTs do not exhibit special electrical properties, our flexible TFT microprocessors work very well in wide voltage and frequency ranges, and reduce energy consumption dramatically. We have seen a best fit between the handshake asynchronous circuits and polysilicon TFTs. The polysilicon TFT asynchronous microprocessors will soon become key devices in the nascent flexible microelectronics industry.

7. Conclusions

TFT technology is advancing by the day and will become a part of the semiconductor industry in the not-too-distant future. The combination of TFT and Suftla technologies will usher in a new era of

life-enhancing flexible microelectronics. In this paper we have reviewed the history of flexible microelectronics and have shown convincing progress.

The world's first plastic asynchronous TFT microprocessor is presented as an example of the progress of flexible microelectronics. The handshake asynchronous circuit is ideal for flexible microelectronics and is used in the TFT microprocessor, because it satisfies all the requirements posed by the TFT LSI circuits on plastic. This result demonstrates the tremendous potential of polysilicon TFT technology and hints at the promise of a future flexible microelectronics industry.

References

- [1] S. Morozumi, K. Oguchi, T. Misawa, R. Araki and H. Ohshima: *SID 84* (1984) p. 316.
- [2] H. Hara, M. Sakurai, M. Miyasaka, S. W. B. Tam, S. Inoue and T. Shimoda: *European Solid-State Circuits Conference ESSCIRC 04* (2004) p. 403.
- [3] T. Shimoda and S. Inoue: *IEDM 99* (1999) p. 289.
- [4] S. Utsunomiya, S. Inoue and T. Shimoda: *SID 00* (2000) p. 916.
- [5] S. Utsunomiya, T. Saeki, S. Inoue and T. Shimoda: *Asia Display 01* (2001) p. 339.
- [6] S. Utsunomiya, T. Kamakura, M. Kasuga, M. Kimura, W. Miyazawa, S. Inoue and T. Shimoda: *Eurodisplay 02* (2002) p. 79.
- [7] S. Utsunomiya, T. Kamakura, M. Kasuga, M. Kimura, W. Miyazawa, S. Inoue and T. Shimoda: *SID 03* (2003) p. 864.
- [8] M. Miyasaka, H. Hara, H. Takao, S. Tam, R. Payne, P. Rajalingham, S. Inoue and T. Shimoda: *Asia Display IMID 04* (2004) p. 145.
- [9] A. Miyazaki, H. Kawai, M. Miyasaka, S. Inoue and T. Shimoda: *Asia Display IMID 04* (2004) p. 153.
- [10] N. Karaki, T. Nanmoto, H. Ebihara, S. Utsunomiya, S. Inoue and T. Shimoda: *ISSCC 05* (2005) p. 272
- [11] M. Miyasaka, M. Hogyoku, S. Inoue, T. Shimoda and J. Stoemenos: *AMLCD 99* (1999) p. 257.
- [12] S. Inoue, H. Ohshima and T. Shimoda: *Jpn. J. Appl. Phys.* **41**, (2002) p. 6313.

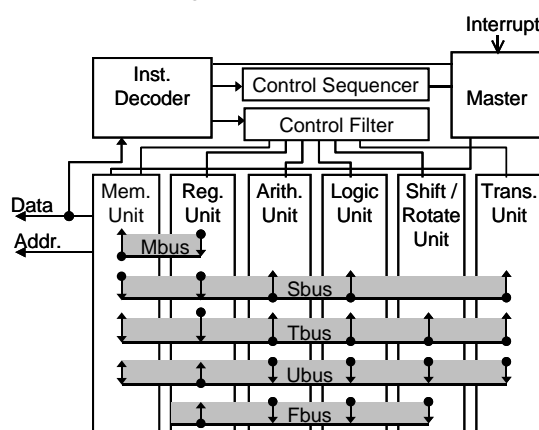


Fig. 5 Core architecture of TFT asynchronous microprocessors

