Sensor and Circuit Solutions for Organic Flexible

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Abstract

This paper describes several sensor and circuit solutions for organic flexible electronic devices. Organic field effect transistors (OFET) enable low-cost, high-flexibility and large-area which can be utilized to implement smart sensors. These sensors can be in contact with the physical objects of any shape. Furthermore, as the devices are very light and flexible, they can even be placed in contact with the human skins. However, design of organic flexible circuits poses great challenges because of several intrinsic properties of organic materials. Thus, newer circuit techniques need to be adopted for robust operation. We give an overview of various sensor and circuit techniques developed in our research group along with other literature reports.

1. Introduction

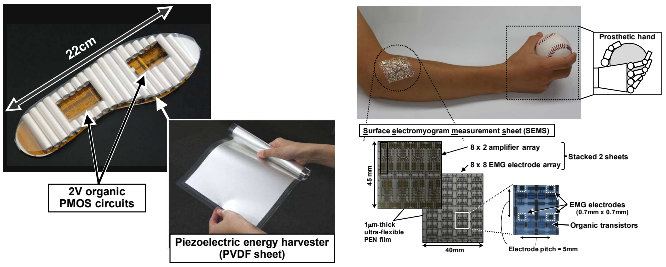
With the emergence of IoT (Internet of Things) era, more and more physical objects are being connected to the internet providing information of our surrounding to enable a more secure and comfortable life. The gap between physical world and cyber world is being narrowed continuously. Newer devices are being investigated that can provide tighter integration between the two worlds. In order to gather information from the physical world, various forms of devices are required including devices capable of sensing large area. Especially for health-care and bio-medical devices, flexible and large area devices that can be attached to human skin for example will provide greater options. Organic transistors can be an attractive option to fulfil the above needs.

Organic transistors can be fabricated on a plastic or a glass sheet, and because of the material properties such transistors are not as rigid as the silicon transistors. Thus, flexible, large- area, low-cost and transparent electronic devices become possible. However, because the materials used for organic transistors are inherently different from silicon, newer circuit solutions need to be established to realize smart sensors with various functions integrated [1, 2].

In Sec. 2, we present several examples of sensor solutions developed in our group. Then, we discuss some digital and analog circuit solutions to realize the sensors in Secs. 3 and 4. Finally, Sec. 5 concludes the paper.

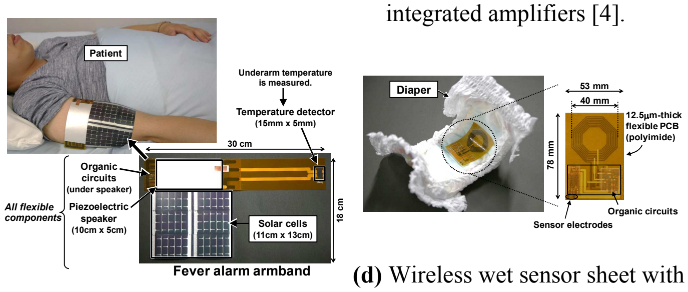
2. Sensor Solutions

As the key feature of organic electronics is its flexibility, they are most suitable for sensor devices that require flexibility. Fig. 1 shows four such sensor devices to show the capability and versatility of organic electronics.



(a) An insole pedometer sheet with piezoelectric energy harvester [3].

(b) An electromyogram measurement sheet with integrated amplifiers [4].



(c) Fever alarm sheet with energy harvesting from solar cell sheet [5].

(d) Wireless wet sensor sheet with wireless power and data transmission capability [6].

Figure 1. Various sensor applications developed in our group.

Fig. 1(a) shows an example of energy harvesting device realized on organic electronics [3]. This is an insole pedometer sheet that is self-powered with energy harvesting capability. The device uses a polyvinylidene difluoride (PVDF) sheet as piezoelectric energy harvester. Then all-pMOS organic circuits are used to utilize the harvested energy and count the stepping. Pseudo-CMOS circuit techniques are used to reshaping the pulses generated from the energy harvester and to implement the counters.

Fig. 1(b) shows an electromyogram measurement sheet which can be used for prosthetic hand control [4]. The key feature is to amplify the small signals from the electrodes. Details of the amplifier techniques will be discussed in Sec. 4.

Fig. 1(c) shows a flexible fever alarm sheet with energy harvesting capability from a flexible solar cell sheet for medical application [5]. The device features an active voltage limiter circuit to protect the device from excess voltage levels. The device also features a piezoelectric speaker sheet for alarming. As the whole system consists of flexible sheets, the device can be used as an armband so that the need for constant monitoring of fever manually is eliminated.

Finally, Fig. 1(d) shows a flexible wet sensor sheet with wireless power and data transmission capability [6]. The device features a coil for power and data transmission, and organic Schottky diodes for rectifying and ESD protection. Using organic diodes, ESD tolerance of more than 2 kV is achieved making the device robust when in contact with human skin.

3. Digital Circuit Solutions

3.1 Problems

The main reason for the tremendous success of silicon CMOS technology is the ease of integrating large number of devices to realize digital circuits that enable robust, low power and high speed computing. However, because of the inherent properties of the organic materials [7], organic devices face the following challenges.

1) Lower mobility and stability for nMOS transistor,
2) Limited number of interconnect layers, and
3) Low reliability and higher variation.

nMOS transistors have much lower mobility than the pMOS counterpart. This poses a great challenge in designing robust and energy-efficient complementary MOS (CMOS) logic implementation. Although it is possible to realize full CMOS circuits using organic materials, researchers have also looked for alternative solutions for higher gain and noise immunity.

3.2 Pseudo-CMOS Circuit

Because of the low mobility of nMOS transistors, CMOS logic gates have low gain. In order to improve the gain, pseudo-CMOS logic topology has been demonstrated that improves the gain by multiple times [8–11]. Fig. 2 shows a general schematic of pseudo-CMOS logic circuit using either pMOS- or nMOS-only transistors [8]. Fig. 3 shows a pseudo-CMOS inverter schematic along with a conventional CMOS inverter schematic. DC characteristics of the two inverter types are also shown in the figure. For the conventional CMOS topology, the gain of the inverter is only 3.2. Whereas, the pseudo-CMOS version shows a gain of as high as 148 [11]. Fig. 3(c) shows the layout and output wave of a three-stage ring oscillator consisting of the pseudo-CMOS inverters of Fig. 3(b). The output frequency is about 156 Hz which could be enough for realizing simple logics to provide intelligence into devices. The pseudo-CMOS logic topology requires a negative supply voltage which may pose additional difficulty. An on-sheet negative voltage generator is proposed in [3]. Fig. 4 shows the schematic and measurement results of the negative voltage generator. In Fig. 4(b), a negative voltage of −1.6 V is generated from a 10 Hz clock with 2 V voltage swing. Fig. 4(c) shows the output voltage against output load current. The voltage generator has a load current capability of several μA which is sufficient to drive transistor gates.

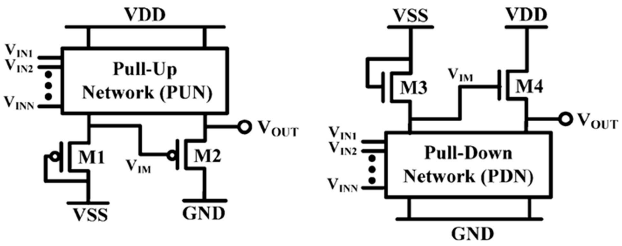
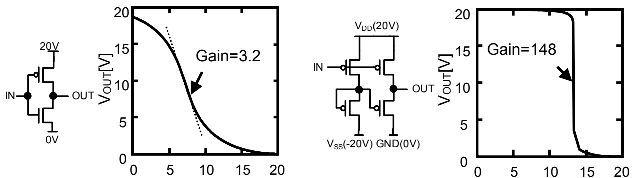
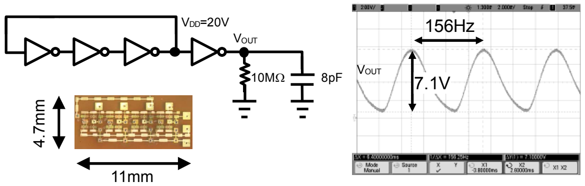


Figure 2. Example of pseudo-CMOS logic gates [8].



(a) V_{OUT}-V_{IN} of conventional CMOS inverter (b) V_{OUT}-V_{IN} of Pseudo-CMOS inverter



(c) Measured circuit, photograph, and waveform of Pseudo-CMOS ring oscillator

Figure 3. Conventional and pseudo-CMOS inverter schematics and their DC characteristics.

Flip-flop is a key building block for digital circuits. Successful operation of a frequency divider using pseudo-CMOS based flip-flop has been demonstrated in [11]. Because of the low conductivity of pMOS transistor switches, boosted gate voltage technique has been applied for robust operation. Fig. 5(a) shows the schematic of the flip-flop where level-shifted clock buffer is used for gate-boosting. The level shift has been achieved by applying −1 V as the lower power rail in the pseudo-CMOS inverter topology. Fig. 5(b) and Fig. 5(c) show the divided waves without and with gate-boosting respectively. Without gate-boosting, retention occurs because of the low conductivity of the switches. Improving the conductivity of switches by gate-boosting, data retention is prevented.

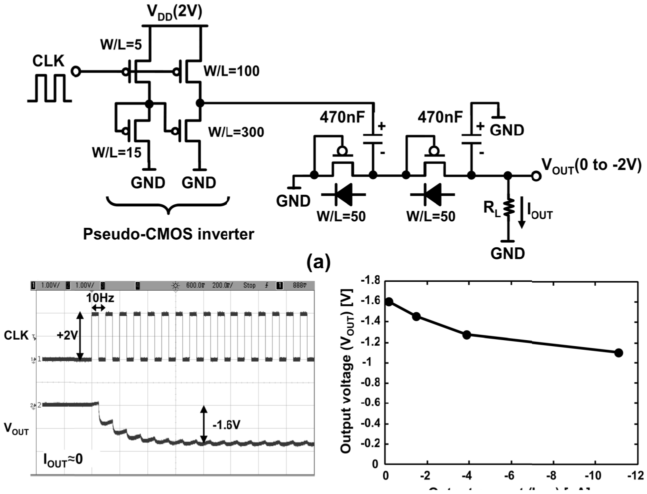


Figure 4. A pseudo-CMOS based negative voltage generator for biasing pseudo-CMOS logic cells [3].

4. Analog Circuit Solutions

4.1 Passive Components

Passive components such as resistor, capacitor and inductor are key components for analog circuits. Compared to the silicon counterpart, organic devices have limitations in material resources. Area-efficient resistors are difficult to realize, but an

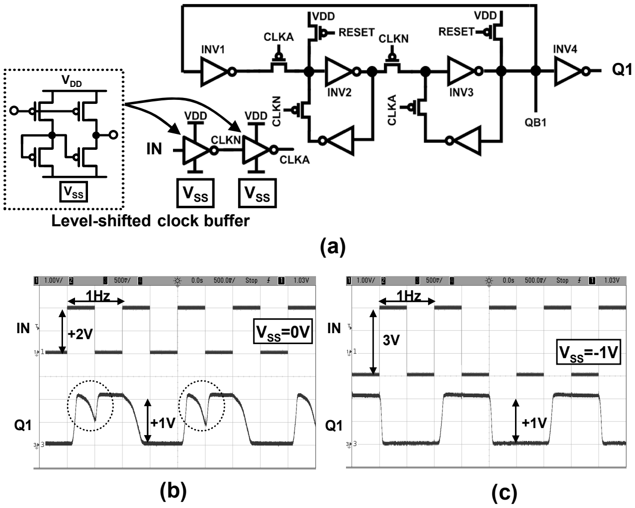


Figure 5. A flip-flop topology using pMOS pass-gates with gate-boosting and level-shifted clock buffers [11].

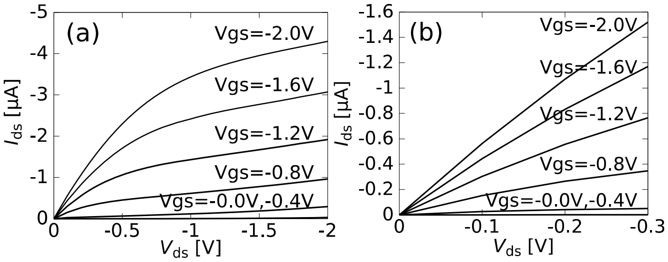


Figure 6. I_{DS}–V_{DS} characteristics of an DNTT organic pMOS transistor with channel length and width of 50 μm and 1600 μm respectively. (a) Large V_{DS}, (b) Small V_{DS}.

workaround is to use the transistors in the triode region as resistors [4]. Fig. 6 shows I_{DS}–V_{DS} characteristics of pMOS transistor under large and small V_{DS} regions. Fig. 6(b) shows that pMOS transistor can be used as resistors under small V_{DS} region. Although this workaround has some limitations such as the reduced operating range, high resistance values can be realized because of the intrinsically lower mobility.

Inductors are essential components especially for wireless communication. Because of low material properties, on-sheet inductors are not available. As an alternative, flexible printed circuit board (PCB) can be used where the PCB sheet and the organic sheet are stacked together to realize flexible devices. A successful operation of wireless power and data transmission using stacked inductor sheet is demonstrated in [4]. On-sheet capacitors can be realized by MIM capacitors. MIM capacitor with capacitance of 700 nF/cm2 is reported in [10].

4.2 Floating Voltage Regulation

Energy harvesting devices such as a solar cell may generate excessive power which may damage the large organic devices. Thus, voltage regulation is required for devices with energy harvesting capability. Conventionally, a diode clamp is used to limit the voltage level. However, because of the material properties, voltage references and Zener diodes are not available. As an alternate solution, a transistor-based active voltage limiter circuit is proposed for voltage regulation [5]. Fig. 7 shows the schematic of the proposed voltage limiter. Here, the first four pMOS transistors from the left realizes a constant voltage generator. Followed by two CMOS inverters and a power pMOS transistor, the circuit acts as a diode but with higher current sensitivity. The right hand figure shows the *I–V* characteristics of the active voltage limiter along with the conventional diode connected pMOS transistor. The active voltage limiter shows higher sensitivity than the conventional diode clamp.

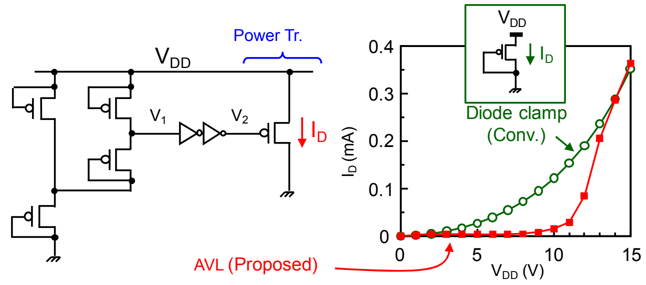


Figure 7. Active voltage limiter acting as a diode [5].

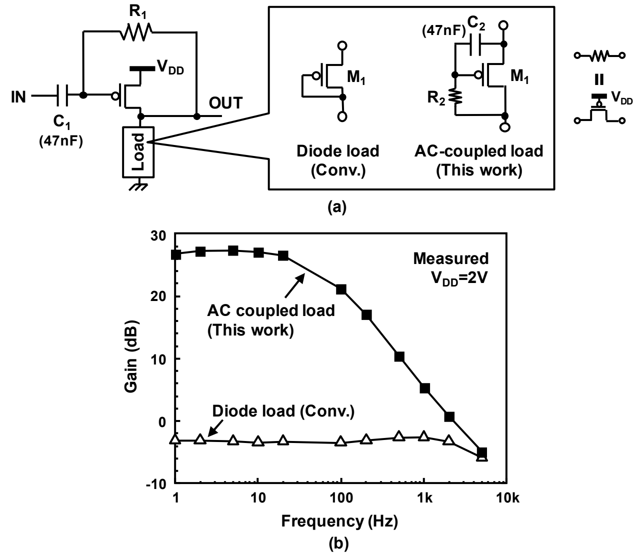


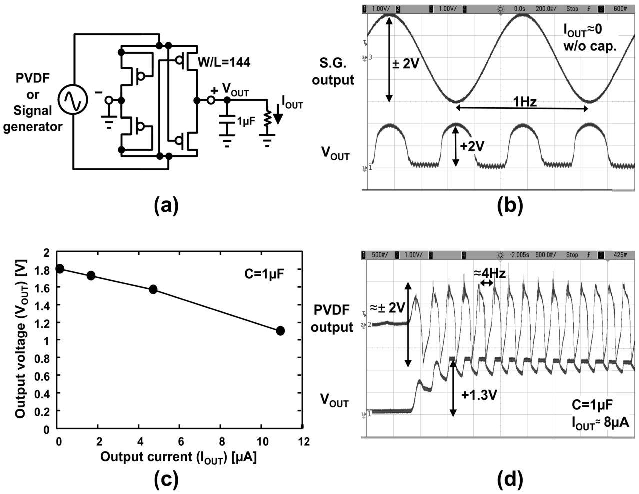
Figure 8. AC coupled load for amplifier gain boosting [4].

4.3 Amplifier with AC Coupled Load

Amplifier is a basic circuit block especially for smart sensor devices as the sensed signals are often small analog signals. Conventional diode connected load does not give the required gain for OFET based amplifiers. In order to improve amplifier's gain and performance, an AC-coupled load technique is proposed [4]. Fig. 8(a) shows an amplifier schematic, and Fig. 8(b) shows the gain of the amplifier with two types of load. One is the diode connected pMOS load and the other is the proposed AC-coupled load. As explained in [4], amplifier with AC-coupled load shows larger gain which is demonstrated in the figure. However, AC-coupled load has a disadvantage that the gain decreases at low frequency region. The lower cut-off frequency is determined by R_2C_2, thus their values need to be set to meet application requirements.

4.4 pMOS-only Rectifier

For wireless power and data transmission transponders, rectifying circuits are required. Fig. 9 shows a pMOS-only rectifier circuit [11]. Cross-coupled topology is used here instead of conventional diode-connected topology to improve the driving current. Thus, by adopting circuit topology accordingly, performances of analog circuits can be increased.



(a) (b)

(c) (d)

Figure 9. pMOS-only rectifier topology [11].

4.5 Others

Besides the above discussed analog design solutions, researchers have developed various analog circuit blocks. For example, a current steering based digital-to-analog converter is developed in [12]. A differential amplifier is proposed in [13]. With more understanding of the organic transistors and with the improvement in their performances, more innovative analog circuit blocks are expected to be developed.

5. Conclusion

We have reviewed various sensor solutions for flexible electronics using organic field effect transistors. Various circuit techniques were discussed to realize the sensors. Because of the differences in organic material properties than their silicon counterpart, digital and analog circuit techniques need to adopt accordingly. We have reviewed the digital circuit solutions that use pseudo-CMOS techniques. We have also shown various analog techniques that can be used to improve gain and other circuit characteristics. With the help of such circuit techniques, robust operation of flexible electronics can be achieved which can make way for a wide variety of sensor applications in the IoT era.

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