

# Design for Mixed Circuits of Organic FETs and Plastic MEMS Switches for Wireless Power Transmission Sheet

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**Abstract**— Design innovations to overcome the shortcomings of a wireless power transmission sheet made with plastic MEMS switches and OFET for printable low-cost electronics are shown. The mixed circuits of MEMS switches and OFETs with two different frequencies reduce the number of coil sheets from 2 to 1. OFET level-shifters, with the current-source loads with enhancement/depletion mixed threshold voltages realized by controlling the back-gate voltage, bridge the operation voltage gap between silicon VLSIs (below 5 V) and OFETs/MEMS (above 40 V).

## I. INTRODUCTION

A wireless power delivery system to electronic objects scattered over tables, walls and ceiling will form an infrastructure necessary for ubiquitous electronics, wireless sensor network and ambient intelligence. A first step toward this goal has been reported as a wireless power transmission sheet [1]. Although the device demonstrated the feasibility of such a system, there were several limitations and drawbacks in practical use. This paper describes design innovations [2] to overcome the shortcomings of a wireless power transmission sheet made with plastic MEMS switches and organic FETs (OFET) circuits suitable for printable low-cost electronics. By the novel design solutions, the sheet reduces the number of coil arrays, and takes 5V digital input by using newly developed level shifter with adaptive biasing and organic analog circuits

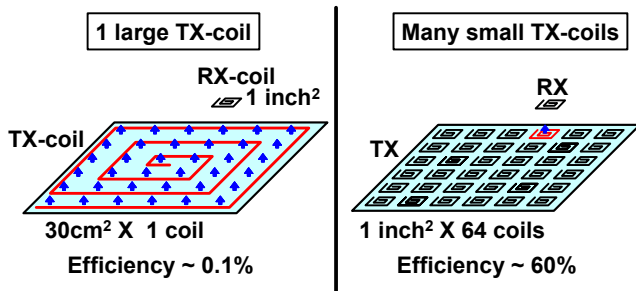
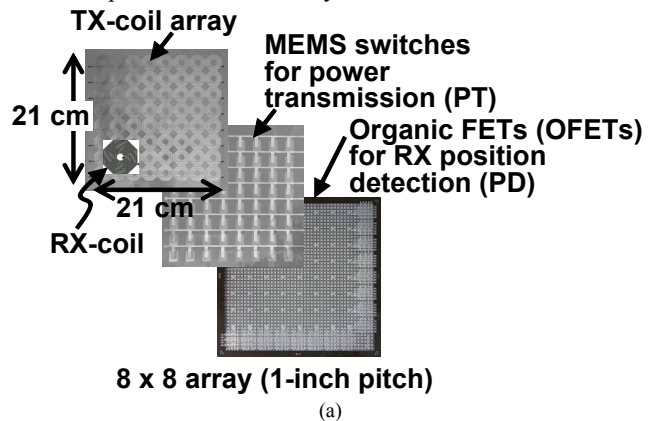


Fig. 1. Power transmission efficiency in two different TX-coils.

which achieves higher gain than a previously reported OFET amplifier.

## II. WIRELESS POWER TRANSMISSION SHEET

The principle of the wireless power transmission is based on an array of coils (TX-coil) made on a plastic sheet which is selectively driven by plastic MEMS switches and is coupled magnetically with a receiver coil (RX-coil) mounted on a power receiving object. Fig. 1 shows the comparison of the power transmission efficiency for a large TX-coil and many small TX-coils. The measured power transmission efficiency of the large TX-coil is 0.1%, while that of the many small TX-coils is 60%. The segmentation and selective activation of TX-coils prevent the efficiency loss. Position detection of the



Switch	Speed	On-resistance
MEMS	~ 1Hz	< 10Ω
OFETs	> 100Hz	> 1kΩ

(b)

Fig. 2. (a) Device structures of wireless power transmission sheet. (b) Speed and on-resistance of MEMS switches and organic FETs. They are complementary switches.

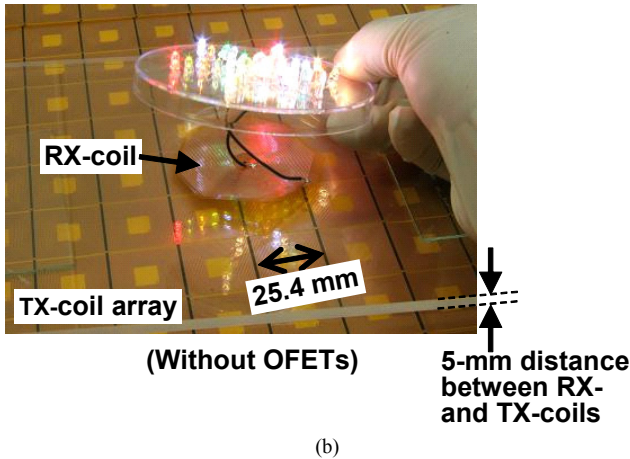
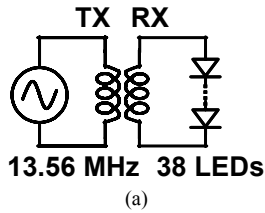


Fig. 3. Wireless power transmission to 38 LEDs. (a) Measurement setup. (b) Demonstration.

receiving object is needed for the selective activation of TX-coils. The position detection is carried out by scanning through many TX-coils to check if an RX-coil exists above a TX-coil by means of impedance change. Fig. 2 (a) shows the device structures of wireless power transmission sheet. Three 21-cm-square plastic sheets are stacked. Each sheet has 8 x 8 array of TX-coil, MEMS switches, and OFETs with 1-inch pitch. Fig. 2 (b) shows the comparison of the speed and the on-resistance of MEMS switches and OFETs. The MEMS switches and OFETs are complementary switches. The MEMS switches are used for the power transmission because they can transfer amperes of current but the switching speed is 1 Hz. In contrast, OFETs are used for the RX position detection because the switching speed of OFETs is more than 100 Hz but the on-resistance is more than 1 k $\Omega$ . Fig. 3 (a) shows the measurement setup for the wireless power transmission to 38 LEDs. Fig. 3 (b) shows the demonstration of the wireless

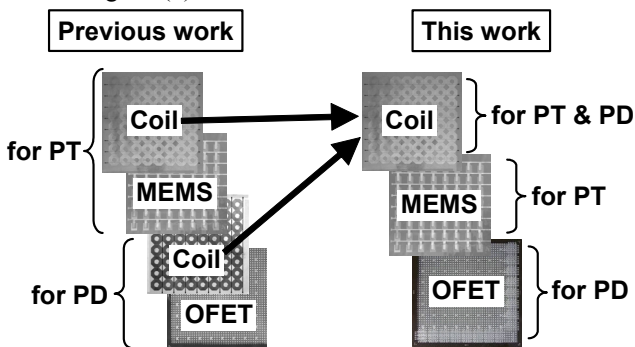


Fig. 4. Shared coil sheet. In the previous work [1], two coil sheets for the power transmission (PT) and the RX position detection (PD) are required. In this work, the developed circuits enabled a shared coil sheet for PT and PD.

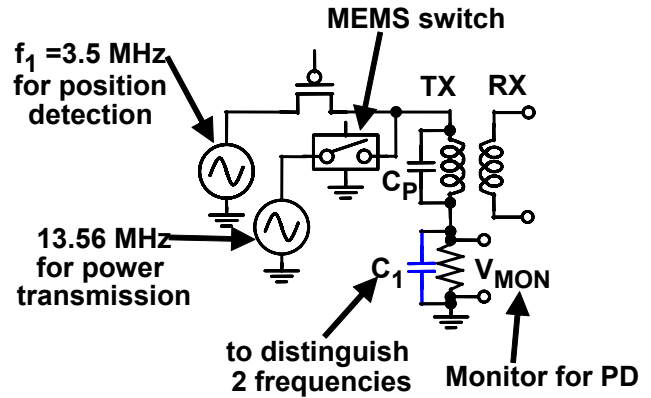


Fig. 5. Mixed circuits of MEMS and OFETs for shared coil.

power transmission. The distance between RX-coil and TX-coils was 5 mm.

### III. SHARED COIL SHEET

Fig. 4 shows the comparison of the sheet configuration of our previous work [1] and this work. The sheet of TX-coil array for the power transmission and the coil array for the position detection were separately fabricated and stacked in the previous implementation. The separate coil sheets stacked together, however, increase the fabrication cost and reduce the position detection efficiency because the power transmission coils sit over the position detection coils. In order to solve the problems, new circuits are developed to enable a shared coil sheet for the power transmission and the RX position detection. Fig. 5 shows the developed mixed circuits of MEMS switches and OFETs for the shared coil sheet. The circuits use two different frequencies and carefully eliminate interference of the two functions: the power transmission and the position detection. The circuit makes use of the fact that the conductivity of MEMS switches is more than  $10^2$  higher than that of OFETs. Thus, the OFET doesn't degrade the power transmission efficiency by shorting two frequency signal

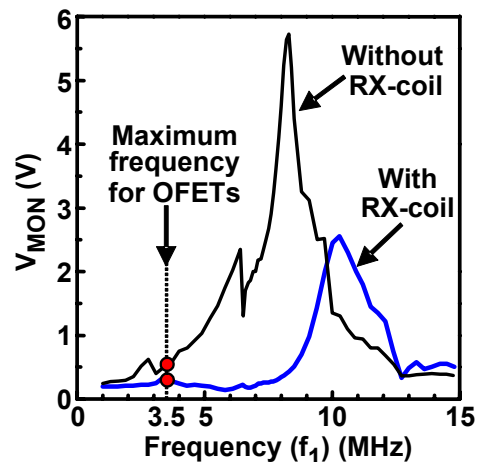


Fig. 6. Measured position detection frequency dependence of monitor voltage with and without RX-coil. 3.5 MHz was used due to the speed limitation of OFETs.

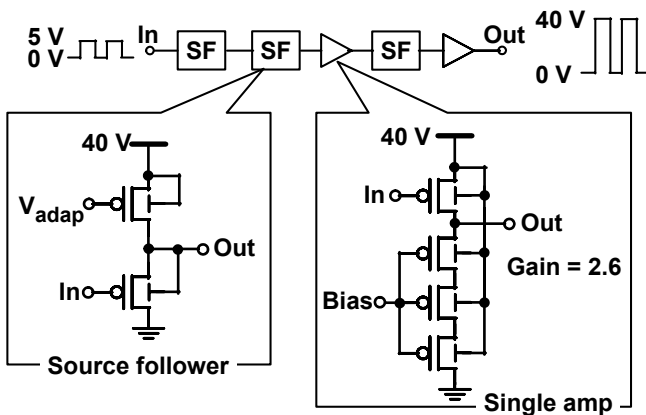


Fig. 7. Original OFET level shifters from 5 V to 40 V. Only pMOS FETs are used.

sources.  $C_1$  is added to decrease the impedance at 13.56 MHz (power transmission frequency) to improve the power efficiency while monitoring the impedance change for 3.5MHz (position detection frequency).  $C_p$  is added to increase the position detection sensitivity by peaking the impedance by LC resonance. As shown in Fig. 6, the measured resonant frequency of  $V_{MON}$  for the position detection system is around 8 MHz to 10 MHz, which is beyond the cutoff frequency of OFETs (3.5 MHz). As seen from Fig. 6, in order to increase the sensitivity for the position detection, the frequency used for position detection is higher the better. Thus 3.5MHz is chosen as the frequency for the position detection.

#### IV. OFET LEVEL SHIFTERS

The integration of the silicon LSIs, OFETs, and MEMS devices is necessary in this power transmission system. Direct digital drive of OFETs and MEMS by silicon LSIs is, however, difficult, because there is large discrepancy in the operation voltage between LSIs (below 5 V) and OFETs/MEMS (above 40 V). Therefore, OFET level-shifters from 5 V to 40 V are developed. Fig. 7 shows the original OFET level shifter circuits. The DC level of the input for the single amplifier is adjusted by tuning the bias voltage of the source follower. The

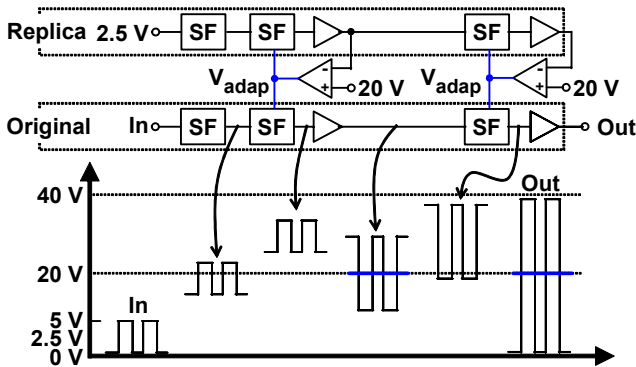


Fig. 8. OFET level shifters with replica circuits for adaptive biasing to deal with PVT variations. The lower figure shows the voltage waveforms of each node.

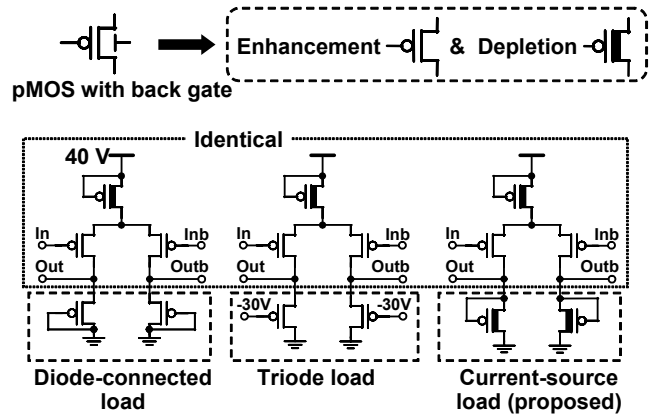


Fig. 9. Three differential amplifiers with different loads. Organic pMOS FETs with back gates achieve both enhancement mode and depletion mode operations by changing the back gate bias.

circuits in Fig. 7 are not robust against PVT variations. Fig. 8 shows the OFET level shifters with replica circuits for adaptive biasing to deal with the PVT variations. Fig. 8 also shows the voltage waveforms of each node in the level shifters. It should be noted that the circuits in Figs. 7 and 8 are pMOS-only design, because nMOSFETs are not commonly available in the OFET designs. In the pMOS-only design, it is difficult to obtain the high gain in the amplifiers. The high gain differential amplifiers in Fig. 8 are the key circuits for the adaptive biasing. Fig. 9 shows three differential amplifiers with different loads to find the high gain circuit topologies. Organic pMOS FETs with back gates [3] achieve both enhancement mode and depletion mode operations by changing the back gate bias. Fig. 10 shows SPICE-simulated gain comparison of differential amplifiers in Fig. 9. Current-source load achieved the highest gain, because the output impedance of the current-source load is the highest. Figs. 11 (a) and (b) show the fabricated differential amplifiers with current-source load with enhancement/depletion mixed threshold voltages realized by controlling the back-gate voltage [3]. The chip area is 2.9 mm by 4.9 mm. The gate length of all OFETs is 50  $\mu\text{m}$ . Fig. 11 (c) shows the measured characteristics of the differential amplifiers. The gain of 6.4 is achieved, which is higher than 2.3 for an organic analog amplifier reported in [4]. Figs. 12 (a) and (b) show the

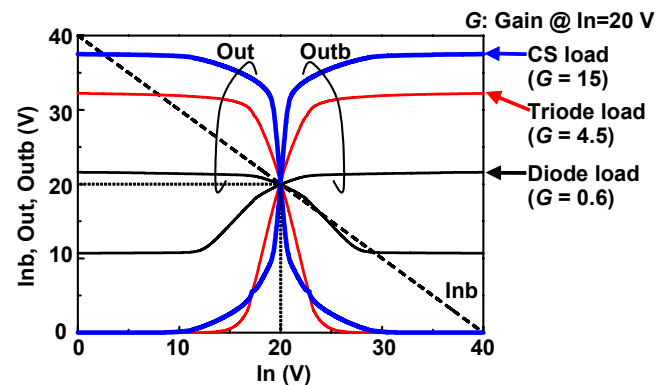


Fig. 10. Simulated gain comparison of differential amplifiers with different loads. Current-source load achieved the highest gain.

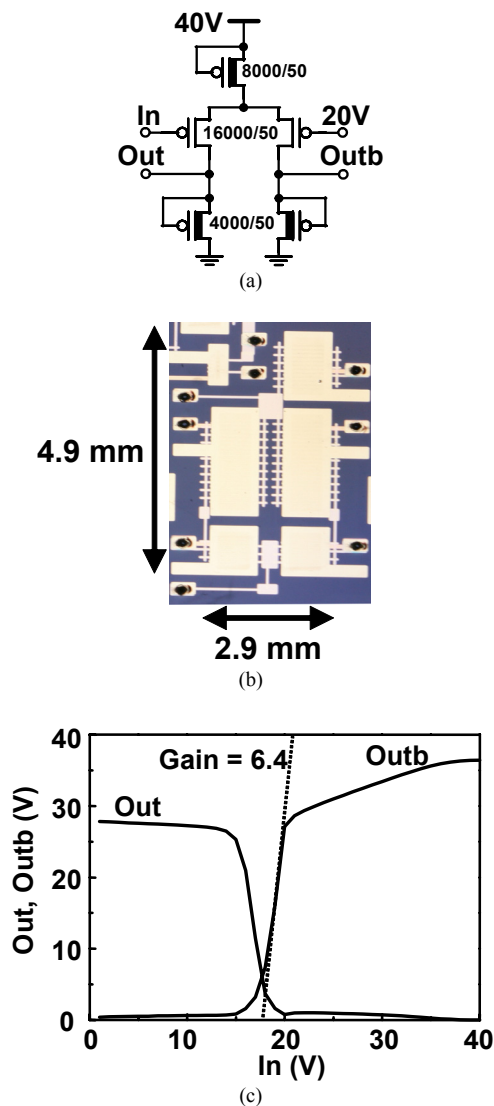


Fig. 11. Differential amplifiers with current-source load. (a) Circuit schematic. (b) Chip micrograph. (c) Measured characteristics.

fabricated adaptive biasing circuits used in the OFET level shifters. The chip area is 6.4 mm by 22.2 mm. Fig. 12 (c) shows the measured characteristics of the adaptive biasing. The developed high gain differential amplifier contributes to the successful feedback control.

## V. CONCLUSION

Design innovations to overcome the shortcomings of a wireless power transmission sheet made with plastic MEMS switches and OFET for printable low-cost electronics are shown. The mixed circuits of MEMS switches and OFETs with two different frequencies (13.56 MHz and 3.5 MHz) reduce the number of coil sheets from 2 to 1. OFET level-shifters, from 5 V to 40 V with the current-source loads with enhancement/depletion mixed threshold voltages realized by controlling the back-gate voltage, bridge the operation voltage gap between silicon VLSIs (below 5 V) and

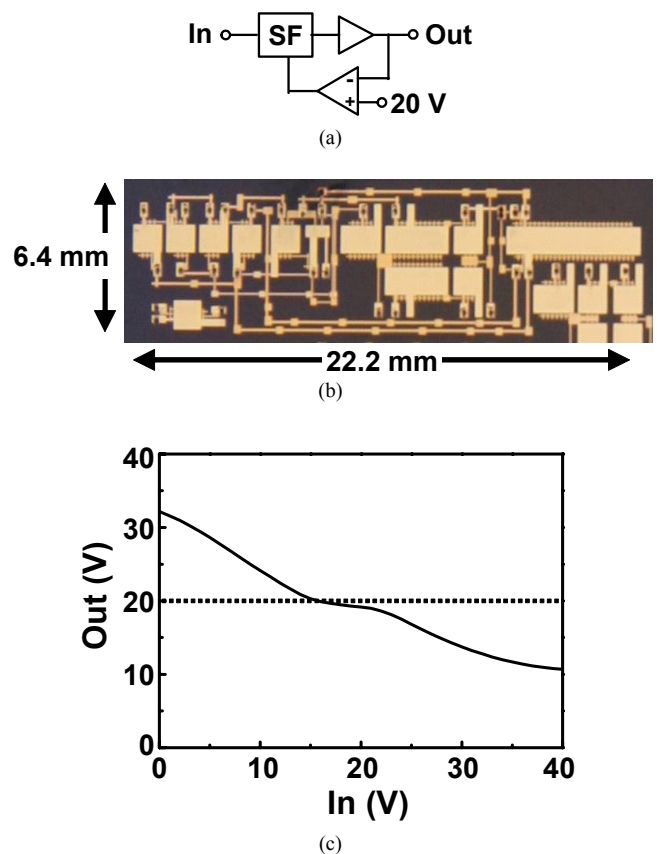


Fig. 12. Adaptive biasing used in the OFET level shifters. (a) Circuit schematic. (b) Chip micrograph. (c) Measured characteristics.

OFETs/MEMS (above 40 V).

## ACKNOWLEDGMENT

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