Synergetic p+n Field-Effect Transistor Circuits for ppb-Level Xylene Detection

Xinyuan Zhou, Ying Wang, Zhou Wang, Liping Yang, Xiaofeng Wu, Ning Han, and Yunfa Chen

Abstract—Nowadays, xylene is not only one major air pollutant which threatens human health even if its concentration is lower than the human olfactory threshold of 470 ppb, but also one of the typical gases exhaled by the lung cancer patients with a criterion of 10-20 ppb. However, in situ detection of the ppb-level xylene for air quality monitoring and breath analysis remains challenging using the easily fabricated and low cost metal oxide semiconductor gas sensors. Herein, a synergetic p+n field effect transistor (FET) amplification circuit is designed to detect the ppb level xylene. By optimizing the load resistor ($R_L$) and the p- and n-FET coupling effect, a magnification factor ($\sim$7.5) is obtained. This amplification circuit decreases the detection limit of TGS2602 sensor to $\sim$10 ppb xylene with apparent response of about 2.3 and voltage change of $>0.5$ V, promising for air quality monitoring (the highest permissive limit of 42 ppb) and breath analysis (the threshold of lung cancer 10–20 ppb). The mechanism is that the matched couple of p+ n FETs work synchronically when their ($R_L + R_{FET}$)–$I$ curves nearly coincide with each other. All those results show the prospect of ppb level gas detection with MOX sensors using the synergetic p+n FET amplification circuit.

Index Terms—Environment and health, field effect transistor, trace concentration xylene, amplification effect, metal oxide semiconductor sensor.

I. INTRODUCTION

XYLENE is one of the most important industrial solvents used for paints, adhesive materials, etc. As a result, it is one of the most representative and ubiquitous indoor toxic gases that are emitted from the indoor decorations and will induce various symptoms, including irritation of the skin, eyes, and respiratory system even at low concentrations [1], [2]. The highest permissive detection limit is therefore strictly limited all over the world, such as the limit of 0.2 mg/m$^3$ ($\sim$42 ppb) in China (GB/T 18883-2002). In the meanwhile, xylene is also one of the typical biodegradable substances (benzene derivatives) related to lung cancer with a criterion of 10-20 ppb [3], as examined by many measurements such as colormetric device by Zhao et al. [4] gas chromatography by Oguma et al. [5] and Ma et al. [6]. Therefore, fast and effectively detecting xylene in ppb level is important and necessary as to monitoring the indoor air quality and also to fast screening the disease [7]–[10]. Although precise and reliable xylene detection can be realized by gas chromatograph spectroscopy [11]–[13] and fluorescence spectroscopy [14] etc., there are some major hurdles for real-time monitoring in sampling, high cost, and prolonged analysis time. Therefore, more and more attention has been paid to the metal oxide semiconductor (MOX) gas sensors due to their advantages of low cost, facile method, easy fabrication and real time monitoring [15]–[21]. However, though MOX sensors are successful in ppm level gas detection such as ethanol [22], [23], acetone [24]–[26], CO [27], [28] etc., it is still challenging for MOX sensors to detect xylene at ppb level, due to the relatively low response at this trace concentration.

To enhance the gas response of MOX sensors, developing highly sensitive MOX materials is widely investigated. And many oxide semiconductors have been synthesized by designing the hierarchical structure and heterostructures, including $a$-MoO$_3$/α-Fe$_2$O$_3$ heterostructures [29], Pd-loaded SnO$_2$ yolk–shell spheres [30], Pd-loaded Co$_3$O$_4$ hollow nanostructures [31], Ni-doped TiO$_2$ bowl-like submicron particles [32], Co-doped branched ZnO nanowires [33], Cr-doped NiO hierarchical nanostructures [34] and double-layered metal-oxide thin film [35]. Though these researches make the xylene MOX sensors more sensitive at ppm level, there is still few MOX sensors reported in the literature capable to detect the xylene at ppb level, nor can most of commercial sensors. And recently, pre-concentrator is developed to detect benzene with response of 1.2 to 100 ppb [36].

From the electronics viewpoint, electronic interfaces are widely investigated and the voltage signal of MOX sensors can be amplified by operational amplifier [37]–[40]. However, the integrated circuits should be complicatedly designed as most MOX sensors are working at a low voltage baseline and then giving a signal of high voltage, and special care should be taken to the noise filtering. All these are considered by the application engineers and the complex circuit design and integration would degenerate the advantage of easy-fabrication and low-cost of MOX sensors. And Wang et al. have developed p+n combined gas sensor array to enhance the response of single p or n type gas sensor [41], which however is not
The value of $R_L$ is well chosen so as to make the p-type RS that generates the signal apparent. Response of 5.4. Further detection limit of less than 1.0 V is obtained for 20 ppb xylene, corresponding to an example. Using this sensor circuit, absolute voltage output sensors taking commercial sensor (Figaro TGS2602, Japan) as amplification circuit to increase the voltage signal of MOX sensors. In this study, p-FET analogue amplification circuit is developed. However, differing from traditional signal of MOX sensors. In this study, p-FET and n-FET are synergistically combined to design the amplification circuit as shown in Figure 1 in an aim to enhance the amplification factor. Similarly, both p- and n-FETs are at ON state using appropriate $R_L$. And in contact with xylene, both $|V_{GS}|$ of the two FETs will increase to turn OFF them. Obviously, both of p-type and n-type FETs amplify the $V_{OUT}$ synchronically, which causes larger $V_{OUT}$ than those of single p- and n-FET amplification circuit, not to say the traditional non-amplified circuits.

**III. EXPERIMENTAL**

Xylene gas sensors (Figaro TGS2602, Japan) are bought from the market, and so do the commercial FETs, which are 2SK163 (Hitachi, Japan), 2SK544 (Sanyo, Japan), 2SK30ATM (Toshiba, Japan), 2SJ45 (NEC, Japan), 2SJ44 (NEC, Japan), and 2SJ164 (Panasonic, Japan). All the electronic devices above are used without any modification. The $I_{DS} - V_{DS}$ and $I_{DS} - V_{GS}$ curves of the FETs are measured by Keithley 4200 semiconductor analyzer. The gas sensing property is measured using static measurement system designed for sensor products (Hanwei WS-30A, China) as details reported in the literature [43]–[46]. Load resistance card is the standard accessory of the system, and the FET is soldered onto the resistance card with D, S, and G electrodes shown in Figure 1. Different xylene concentrations ($\geq 0.5$ ppm) are generated by dropping certain amounts of the liquid xylene with a micro syringe onto an evaporator in the test chamber (total volume 18 L). Xylene gases with 0.02, 0.04, 0.1 and 0.2 ppm are produced by adding certain volume of 20 ppm standard gas into the chamber. $R_{S_a}$ and $R_{S_g}$ are sensor resistances ($R_S$) in air and in xylene gas, which are calculated as:

$$R_{S_a} = R_L(V_{CC} - V_{OUT,a})/V_{OUT,a}. \quad (1)$$

$$R_{S_g} = R_L(V_{CC} - V_{OUT,g})/V_{OUT,g}. \quad (2)$$

where $V_{CC}$ is 5 V, $R_L$ is the load resistance and $V_{OUT}$ is the measured voltage response. Then response in traditional circuit is defined as:

$$R_{S_a}/R_{S_g} = (V_{CC}/V_{OUT,a} - 1)/(V_{CC}/V_{OUT,g} - 1) \quad (3)$$

As to FET amplification circuit, $R_{S_a}$ and $R_{S_g}$ are calculated in same way:

$$R_{S_a} = (R_L + R_{FET,a})(V_{CC} - V_{OUT,a})/V_{OUT,a}. \quad (4)$$

$$R_{S_g} = (R_L + R_{FET,g})(V_{CC} - V_{OUT,g})/V_{OUT,g}. \quad (5)$$

Thus the magnification factor (MF) is $(R_L + R_{FET,g})/(R_L + R_{FET,a})$. i.e. resistance change of the load $(R_L + R_{FET})$.

**IV. RESULTS AND DISCUSSION**

**A. p-FET Amplification Circuit**

Figaro TGS2602 MOX sensor is developed for toluene, with no response data to xylene in the manual. To estimate the source voltage ($V_{GS}$) of the p-type FET, which will turn off the p-type FET, i.e. the resistance of the p-FET will increase dramatically. The increased p-FET resistance gives feedback to the circuit again to enhance the $V_{OUT}$, higher than that without the p-FET. Using this principle, n-FET amplification circuit is also designed as reported in previous study [42].

Then, the p-FET and n-FET are synergistically combined to design the amplification circuit as shown in Figure 1 in an aim to enhance the amplification factor. Similarly, both p- and n-FETs are at ON state using appropriate $R_L$. And in contact with xylene, both $|V_{GS}|$ of the two FETs will increase to turn OFF them. Obviously, both of p-type and n-type FETs amplify the $V_{OUT}$ synchronically, which causes larger $V_{OUT}$ than those of single p- and n-FET amplification circuit, not to say the traditional non-amplified circuits.

![Fig. 1. Design scheme of the conventional electric circuit, designed single p- and n-FET amplification circuit and synergetic p+n amplification circuit for MOX xylene sensors.](image-url)
4.2 V is the optimum heating voltage adopted in the following experiments. Different voltages from 3.6 to 5.0 V as shown in Figure 2. Therefore, the curves of FETs 2SJ44, 2SJ45 and 2SJ164, (b) response of TGS2602 to 1 ppm xylene gas is tested in the traditional circuit without FET (statistics of 20 sensors) when the gas sensor is heated by heating voltages from 3.6 to 5.0 V with a step of 0.2 V.

Fig. 2. Response curve of TGS2602 to 1 ppm xylene gas in the traditional circuit without FET (statistics of 20 sensors) when the gas sensor is heated by heating voltages from 3.6 to 5.0 V with a step of 0.2 V.

Fig. 3. Amplification effect of p-FET amplification circuits: (a) Ids-Vgs curves of FETs 2SJ44, 2SJ45 and 2SJ164, (b) response of TGS2602 to xylene from 0.1 to 3 ppm in the electric circuit with and without FET 2SJ44, (c) magnification factors of the amplification circuit with FET 2SJ44, and (d) the curves of (R_L + R_RFET) – 1 by connecting resistors of R_L = 4.7, 6.0 and 10.0 kΩ. The intersection points with 5/I – R_S curves of FET 2SJ44 at different V GS as shown in Figure 3b. It is clear that responses to xylene from 0.1 to 3 ppm are enhanced greatly by the p-FET amplification circuit. The magnification factors are shown in Figure 3c by testing at least 6 sensors. It illustrates that maximum apparent response and magnification factors are obtained using the 6.0 kΩ resistor when concentrations of xylene are lower than 0.5 ppm. The magnification factors are 3-5 depending on gas concentrations because varied gas concentrations would generate different gate voltages of the FET 2SJ44 and thus make it work on different resistances.

Quantitatively, the magnification factor (MF) is the change of the total resistance (R_L + R_RFET), which can be calculated by the formula (R_L + R_RFETa)/(R_L + R_RFETa) [42]. (R_L + R_RFETa) can be estimated by two methods: the first one is that it is plotted by V_OUT/I, where V_OUT = –V_DS + V_GS from the p-type FET viewpoint in Figure 1. The V_OUT can be estimated by the I_DS – V_DS curves of FET 2SJ44 at different V GS as shown in Fig. S2a. In the meanwhile, in the series circuit of ohmic law R = U/I, (R_L + R_RFETa) can also be calculated by the equation (R_L + R_RFETa) = 5/I – R_S,a as shown in Figure 3d (black line) with typical measured R_S,a = 45 kΩ of the sensor (more details about Figure 3d are shown in Supporting Information Figure S1). The intersection points of these two curves (R_L + R_RFETa) = V_OUT/I = 5/I – R_S,a are the values of (R_L + R_RFETa).

It is found that the value of (R_L + R_RFETa) is about 4.85 kΩ when R_L is 4.7 kΩ with FET 2SJ44 inferring the ON state of the FET with resistance of only 0.15 kΩ. On the other side, when the gas sensor is exposed to 0.5 ppm xylene, the value of R_S,0.5ppm is 6.7 kΩ (response to 0.5 ppm is 10.0 ppm in Figure 3b, and R_S,0.5ppm = 45 kΩ/6.7). Similarly, the value of (R_L + R_RFET,0.5ppm) can be calculated by the intersection points between the curve of (R_L + R_RFET) = 5/I – R_S,0.5ppm in Figure 3d. The value of (R_L + R_RFET,0.5ppm) is about 28.40 kΩ. Thus, the MF is calculated to be 28.40 kΩ/6.7 kΩ = 5.9. It should be noted that when R_L is 6.0 kΩ, there is no intersection points between the curve of (R_L + R_RFET) = 5/I – R_S,0.5ppm. which means that (R_L + R_RFET,0.5ppm) has reached the saturation value 32.47 kΩ and the R_L + R_RFET,0.5ppm value is about 6.40 kΩ as seen in Figure 3d. Thus the MF is 32.47 kΩ/6.4 kΩ = 5.1. Some maximum values of (R_L + R_RFETa) and initial values of (R_L + R_RFETa) are listed in Table 1. Then MF can be easily estimated by the resistance change, as shown in Table 1. It is noticed that...
Fig. 4. Amplification effect of n-FET amplification circuits: (a) $I_{DS}$-$V_{GS}$ curves of FETs 2SK544, 2SK163 and 2SK30ATM, (b) response of TGS2602 to xylene from 0.1 to 3 ppm in the electric circuit with and without FET 2SK544, (c) magnification factors of the amplification circuit with FET 2SK544, and (d) the curves of $(R_L + R_{FET}) - I$ by connecting resistors of $R_L = 4.7, 6.0$ and 10.0 kΩ. The intersection points with $5/I - R_S$, $a$ and $5/I - R_S$, $0.5$ ppm curves are the $(R_L + R_{FET})$ value in 0.5 ppm xylene. These estimated theoretical MF are in good consistence with those observed. Figure 3d shows that the $R_L + R_{FET}$, $a$ value (about 6.40 kΩ) is similar to $R_L = 6.0$ kΩ without FET 2SJ44 (at ON state, $R_{FET}$ is $\sim 0.4$ kΩ). This means the FET has neglectable impact on the baseline in clean air, which is the main reason why this p-FET amplification circuit could not amplify the noise. Therefore, the p-FET amplification circuit can now work well for the MOX sensors from both mechanism and technological aspects, with the largest MF of $\sim 5$.

B. n-FET amplification circuit

The n-FET amplification circuit has been studied in our previous work with similar MF of 5-6 in detection of toluene, acetone and ethanol [42]. In this paper, more n-FETs (2SK163 and 2SK30ATM) are explored in an aim to amplify the apparent response to xylene, with different $R_L$ (4.7, 6.0 and 10.0 kΩ). Figure 4a shows the typical transfer curves of these n-FET devices, which can effectively amplify the apparent response to xylene as compared in Figure 4b. The largest MF is also calculated to be 5-6 as shown in Figure 4c, which is also in good accordance with those theoretically estimated in Figure 4d (more details shown in Figure S2). All these results show the similar amplification effect in detecting xylene using the n-FET 2SK544 compared to p-FET.

C. Synergetic p+n amplification circuit

From Figure 3b, c and Figure 4b, c, it should be noted that maximum response values and magnification factors are obtained using the 6.0 kΩ resistor when concentrations of xylene are lower than 0.5 ppm. Therefore, the value of $R_L$ is chosen to be 6.0 kΩ in the p+n amplification circuit which combines p-type FET 2SJ44 and n-type 2SK544 as connected in Figure 1. As shown in Figure 5a and b, it is obvious that output voltages and apparent response value to xylene are enhanced greatly by the p+n amplification circuits.

The MF curves are shown in Figure 5c by testing at least 6 sensors, where it is obvious that MFs of p+n amplification circuit ($\sim 7.5$) exceed greatly those of single p- and n-FET amplification circuits ($\sim 5$).

To explore more available p+n circuits, three couples of p- and n-FETs with similar threshold voltages and subthreshold swings are adopted to detect the xylene, with apparent responses and MFs shown in Figure 6. It is clearly shown that the couple of 2SJ44 + 2SK544 works more excellently than other two couples of FETs (2SJ45 + 2SK163 and 2SJ164 + 2SK30ATM), as details shown in Figures S3-6 in supporting information. It should be noted that the p- and n-FETs should be well chosen as to be integrated into an effective synergetic p+n amplification circuit. For example, 2SJ44+2SK544 couple has higher MF than those single ones, while 2SJ45+2SK544 couple has similar MF with single ones (Figure S7), meaning only one FET works in this couple. We further study how a p-type FET and an n-type FET could match successfully among various FETs. Figure 7 illustrates $(R_L + R_{FET})$ curves of two p-type FETs (2SJ44 and 2SJ45) and two n-type FETs (2SK544 and 2SK163). It is found that 2SJ45 and 2SK163 FETs match well because their $(R_L + R_{FET})$ curves nearly coincide with each other, and so do 2SJ44 and 2SK544 curves.
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Fig. 6. Amplification effect of synergetic p+n amplification circuit. Comparison of (a) the calculated response and (b) magnification effect among three p+n amplification circuits with a couple of FETs (2SJ44+2SK544, 2SJ45+2SK163, and 2SJ164+2SK30ATM) by connecting resistor of $R_L = 6.0 \, \text{k} \Omega$.

and 2SK544. This guarantees that the matched couple of FETs work synchronically to induce the optimum amplification effect of p+n circuit. Their MFs are listed in Table 1. It should be noted that both p-type 2SJ44 and 2SJ45 have similar transfer curves as shown in Figure 3a and thus are complementary to n-type 2SK544 in traditional CMOS. However, once 2SJ45 and 2SK544 FETs are integrated in p+n amplification circuits, it is expected that 2SJ45 FET will work and become saturated firstly at low current ($< 0.1 \, \text{mA}$) while 2SK544 does not work at the moment seen in Figure 7 and Figure S7 (the two FETs are connected in series and thus should have the same current), which makes failure of the synergetic p+n amplification circuits. Nor can the other combinations of p+n FETs work synergistically to enhance the signal.

In all, the amplification effect in p+n circuit is obtained if $(R_L + R_{FET})$ curves of p- and n-type FETs nearly coincide with each other.

The optimized p+n amplification circuit is then used to test the response to xylene with lower concentration such as 20 and 40 ppb as shown in Figure 8. A significant voltage response can be seen in the response curve in Figure 8a with the couple of FET 2SJ44+2SK544. Otherwise, the voltage change is neglectable to 20 and 40 ppb xylene in the conventional circuit. The apparent responses are calculated in Figure 8b, where it is clear that responses of 5.4, 7.0 and 18.8 are obtained to 20, 40 and 100 ppb xylene, much higher than those without FET. Figure 8c shows the fitting curves versus concentration, which derives the response of response to xy2.3 to 10 ppb xylene.

As the voltage signal is adopted in electronic circuits, we also plotted the voltage signal in Figure 8d. If we set a background error of 0.1 V (noise $< 0.01 \, \text{V}$ as shown in Figure S8) in detecting the voltage, then 0.3 V voltage should be taken as the effective signal ($S/N = 3$). It is clear that the voltage signal is $> 0.5 \, \text{V}$ for the 10 ppb xylene, meaning the good resolution at this level. It should be noted that this detection limit is more than one order of magnitude lower than the human’s olfactory threshold of 470 ppb [49]. China (GB/T 18883-2002) recommends a maximum permitted limit of $0.2 \, \text{mg/m}^3 (42 \, \text{ppb})$ xylene in indoor air. Therefore, whether the xylene concentration is above the standard in indoor air can be easily assessed using the p+n amplification circuit with detection limit of $\sim 10 \, \text{ppb}$. And more importantly, all the electronics can be readily purchased from the market and be integrated easily onto a board.

To measure the cross sensitivity of the sensor, some typical gases are tested in this study including toluene (TGS2602 is designed for toluene in the manual as it is often used as the total organic volatile compounds equivalent concentration for air contaminants [50], [51]), benzene, acetone,
ethanol, formaldehyde and relative humidity (RH) as shown in Figure 9 and Figures S9-13 in supporting information. It is clear that the response to xylene is far higher than those to benzene, toluene, acetone, ethanol and formaldehyde as shown in Figure 9a. Though the response to toluene is up to 20% of that to xylene, the cross sensitivity is not so important as toluene is also one of biomarkers related to lung cancer [3], [47]. However, the cross sensitivity is neglectable to formaldehyde, which is one typical volatile organic compound (VOC) for breast cancer [3], [48]. The largest interference comes from acetone, which however induces only <1/3 of the response to xylene. Last but not least, in a high humid atmosphere of RH 80%, the gas sensing performance to xylene is similar to those in RH 25% as shown in Figure 9b. Therefore, the FET amplification circuits can make TGS2602 gas sensor very helpful for early stage real-time diagnosis of lung cancer.

In short, the p+n amplification circuit could make TGS2602 gas sensors show higher response to xylene than traditional ones. At the same time, the p+n amplification circuits can extend the detection limit of TGS2602 to ∼10 ppb xylene. Data listed in Table 2 show comparison of some typical xylene sensors. It is noticeable that these commercial sensors working in p+n amplification circuits are already ones of the highest responses and most importantly, they can be readily used for trace concentration gas detection integrated in a large scale. It is also noted that the response time of 30-40 s is not influenced by FET amplification circuits as shown in Table S1.

However, recovery time is prolonged by several seconds, which may be due to the superposition of two hysteresis loops in IDS-VGS curves of FETs 2SJ44+2SK544, and without FET by connecting 6.0 kΩ resistor in different humid atmospheres (25% and 80%).

### V. CONCLUSION

The ppb-level xylene detection for air quality monitoring and breath analysis using metal oxide semiconductor (MOX) gas sensors is successfully completed by our proposed synergetic p+n amplification circuits. The amplification mechanism is found to be the resistance change of the FET induced by the gate voltage. Besides, synergetic p+n amplification circuits can not only improve the sensor’s response to different concentrations of xylene, but also decrease the detection limit of TGS2602 sensor to ∼10 ppb xylene. Further study indicates that amplification effect of synergetic p+n circuits is ascribed to the fact that (RL + RFET) curves of p- and n-type FETs nearly coincide with each other, which guarantees that the matched couple of FETs work synchronically. In the meanwhile, the sensor shows also good selectivity over formaldehyde, one typical gas exhaled by breast cancers and relative humidity existing in breath. In a word, the signal amplification circuits above show the advantage in low concentration gas detection in environment and health. And these circuit designs are also promising in other kind of sensors to extend the detection limit to low concentrations.

### TABLE II

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<tr>
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<td>1</td>
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<td>This work</td>
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<td>~1.8 with 2SJ44 and 2SK544</td>
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<td>[29]</td>
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<td>~10</td>
<td>[30]</td>
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REFERENCES


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