GasFETs incorporating conducting polymers as gate materials

J.V. Hatfield [a,*], J.A. Covington [b], J.W. Gardner [b]

[a] *Department Electrical Engineering and Electronics, University of Manchester Institute of Science and Technology, PO Box 88, Manchester M60 1QD, UK*
[b] *Department of Engineering, University of Warwick, Coventry, CV4 7AL, UK*

Abstract

A gas sensitive field effect transistor with a conducting polymer gate is described (polyFET). The devices were fabricated as gateless FETs in an aluminium gate pMOS process. Post-processing steps were performed to provide the gateless devices with polypyrrole gates. On exposing the transistor gates to volatile compounds, the polyFETs experience a change in their threshold voltage which, in an appropriate circuit, manifests itself as a change in drain-source current. A number of results are presented. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: GasFET; Conducting polymer; Work-function; Threshold-voltage; MOSFET

1. Introduction

Gas sensors based on arrays of different conducting polymers have largely concentrated on monitoring the change in resistance which accompanies the polymers exposure to the gas sample under consideration. There are other properties of conducting polymers apart from bulk resistance that change upon exposure to volatile compounds. Blackwood and Josowicz [1], for example, tabulate work function changes on exposure to more than 30 volatiles. They report absolute values as high as 350 meV change. The work function of the gate material of Metal Oxide Silicon Field Effect Transistors (MOSFETs) is one of the factors which determines the threshold voltage of these devices. A discussion of MOSFET device characteristics can be found in Sze [2]. These devices normally operate in the saturation or non-saturation modes described semi quantitatively by Eqs. (1) and (2), respectively.

$$I_{DS} \approx \frac{W}{2L} \mu_o C_i (V_{GS} - V_T)^2 \text{ for } V_{GS} - V_T < V_{DS} \text{ and} \quad (1)$$

$$I_{DS} \approx \frac{W}{L} \mu_o C_i \left[(V_{GS} - V_T) V_{DS} - \frac{1}{2} V_{DS}^2 \right] \text{ for } V_{DS}$$
$$\leq V_{GS} - V_T \quad (2)$$

Here, I_{DS} represents the drain/source current through the transistor and W/L defines the dimensions of the transistor gate. V_T is the threshold voltage. Clearly if V_T changes there will be a corresponding change in I_{DS} provided that V_{GS} and V_{DS} remain constant. The threshold voltage itself is described by an equation of the form:

$$V_T = -\left(\phi_{ms} - \frac{Q_f}{C_i} \right) + 2\psi_B + \frac{\sqrt{4\varepsilon_s q N_A \psi_B}}{C_i} \quad (3)$$

The important term here is ϕ_{ms} as it represents the work function difference between the gate material and silicon.

2. The new polyFET

The present work was motivated by the desire to find simple ways of constructing gasFETs [3]. The gateless pMOS devices that were used in this exploratory work were supplied by the National Microelectronics Research Centre in Cork, Ireland [4]. The chips were supplied on a 4-in. wafer with each chip consisting of two gateless FETs and one FET with an aluminium gate. The team working at UMIST have developed techniques for chemically depositing a base conducting polymer layer from pyrrole vapour (CVD). By using standard photolithographic techniques, the resulting polypyrrole (PPy) thin film can be easily

* Corresponding author. Tel.: +44-161-200-4724; fax: +44-161-200-8946; e-mail: hatfield@fs5.ee.umist.ac.uk
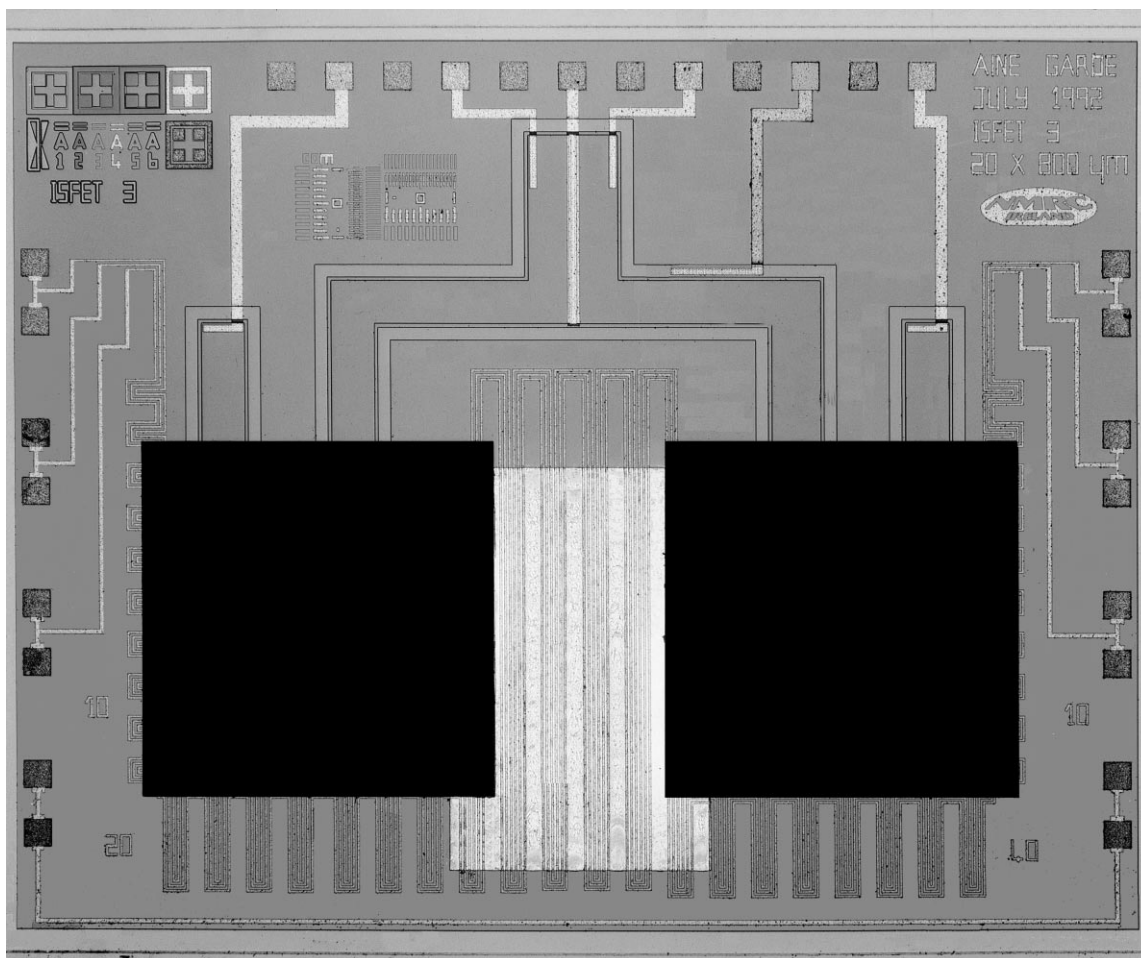
Fig. 1. Photomicrograph of gateless FET chips after fabrication of PPy gates and addition of gate contact. (Chip dimensions approximately 5 mm × 4 mm).
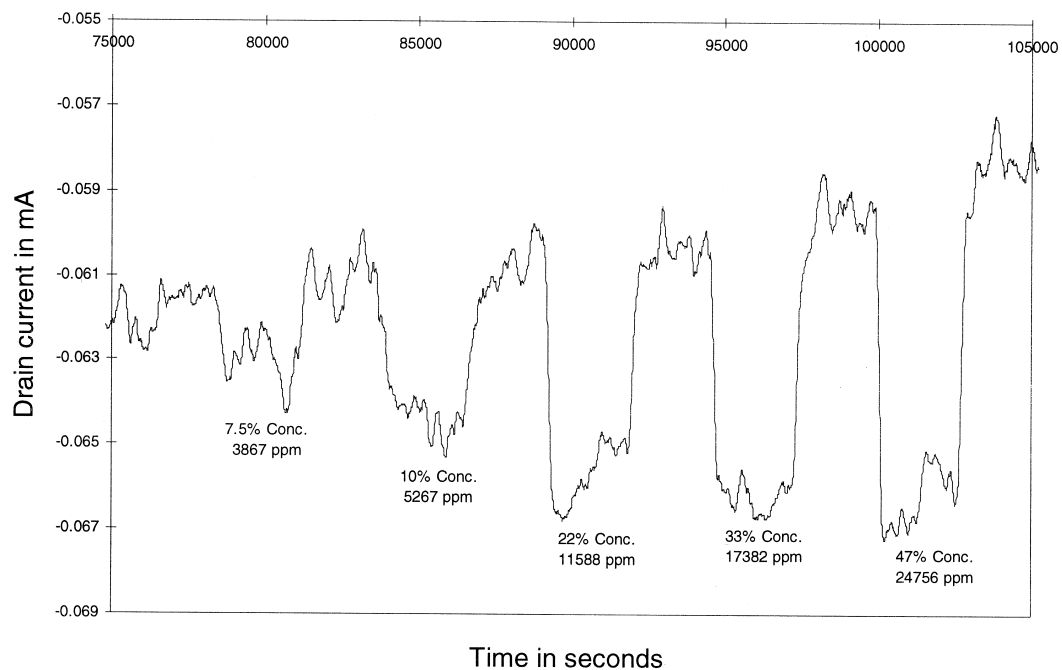

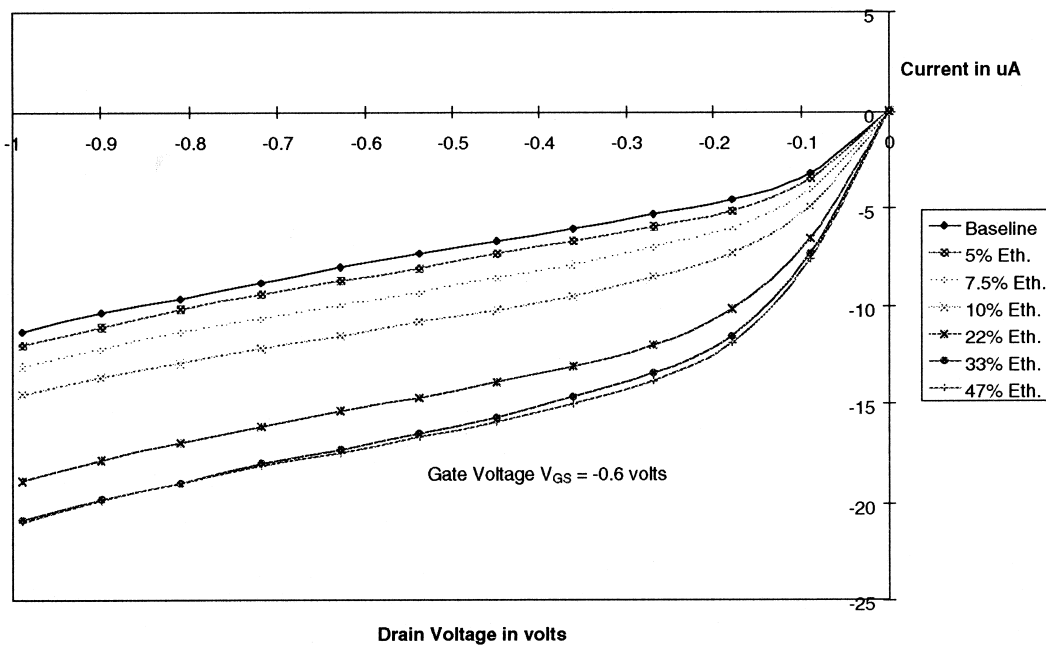Fig. 2. Response of a polyFET to ethanol vapour.

Fig. 3. *I–V* characteristics for a polyFET at different concentrations of ethanol vapour.

etched in an oxygen plasma, [5]. Fig. 1 is a photomicrograph of a processed chip. The black squares are PPy and cover the exposed gates of the two FETs. The resulting polyFETs have gate dimensions of width (W) equal to 400 μm and length (*L*) equal to 20 μm. The PPy, therefore, overlaps the transistor gate by a huge amount. This was purely for convenience and to facilitate an electrical contact to the gates. This latter is achieved by means of the aluminium pad visible between the two PPy gates.

2.1. Testing the polyFET

These devices were tested in an Injection Flow Analysis (IFA) rig developed by one of the authors (JAC). This IFA rig allows the concentration of a volatile organic compound, in vapour form, to be mixed with two air lines; one saturated with water and the other dry to produce an exact concentration of analyte at a specified humidity. The polyFETs were packaged in a 14 pin DIL ceramic package and tested with ethanol at concentrations of 5%, 7.5%, 10%, 22%, 33% and 47% which correspond to 2634, 3687, 5267, 11588, 17382 and 24726 ppm respectively. These sample concentrations were then tested at relative humidities of 10, 22, 33, and 47%. An example of a result of a polyFET at a fixed gate potential is shown in Fig. 2. This was driven with a constant drain and gate voltage of -0.5 V and shows the response at a fixed humidity of 33% RH. As can be seen from this figure, though the signal is small and noisy, the polyFET is responding to the ethanol. The reason for some of the device noise is that the substrate tap on the sensors was compromised while the polymer was being deposited. A direct link to bulk substrate had to be made to allow the devices to operate and this was not an

ideal situation. Also the age of the polymer has reduced the response of the sensors.

The responses manifest themselves as an increase in the drain current in the FET devices. This increase in current can be equated to a reduction in the threshold voltage of the pFET device. The *I–V* characteristics of these devices have also been investigated, an example of which is shown in Fig. 3. This figure shows that the characteristic curves of the polyFET devices has shifted with exposure to ethanol at a fixed gate voltage and that the current through the device has increased.

The drain current increases that are observed is an effect of the change in work function of the MOSFET device, which manifests itself as a change in the threshold voltage, (Eq. (3)). Thus, to analyze the response of the
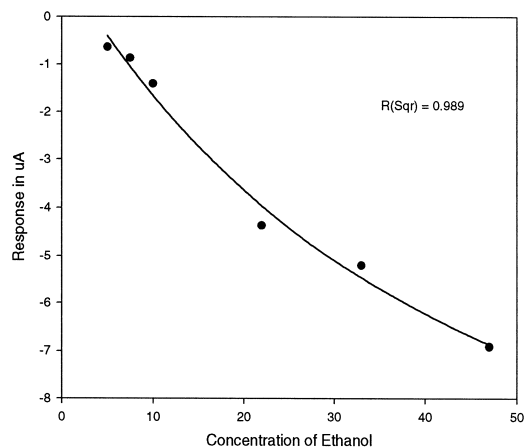

Fig. 4. Langmuir isotherm fit to the response of a polyFET at 22% RH. $V_{GS} = -0.6$ V, $V_{DS} = -0.4$ V.
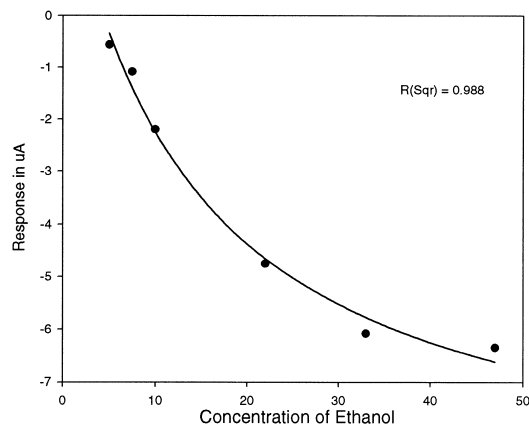
Fig. 5. Langmuir isotherm fit to the response of a polyFET at 10% RH. $V_{GS} = -0.6$ V, $V_{DS} = -0.4$ V.

sensor we equate the change in drain current to the shift in threshold voltage. If we consider the equation, which defines MOSFET operation in the linear region (Eq. (2)), we can write the following expression by considering only the change in threshold voltage to the response of the sensor:

$$\Delta I_{DS} \propto \Delta V_{T} \tag{4}$$

It is possible to consider the responses in the saturated region though this produces a quadratic expression which is more difficult to analyze. An empirical fit to this response curve is given by:

$$\Delta V_{T} = \frac{\Delta V_{max}}{1 + k/\sqrt{C}} \tag{5}$$

where ΔV_{max} is the maximum response and C is the concentration of analyte. A chemical model for this response, which is usually applied to conducting polymers, is a Langmuir isotherm [6] and so its application to a FET device would be:

$$\Delta V_{T} = A \left[\frac{kC}{1 + kC} \right] \tag{6}$$

where k is the ratio of forward and backward reaction rates (i.e., binding constant), A is another constant, and C is the concentration of the analyte as before. This equation describes a model where the amplitude of the response is controlled by the number of free sites available for the gas or vapour to bond to. Thus, as the concentration of vapour rises the corresponding incremental increase in the sensors response gets less. The response of the polyFET devices have been fitted to a Langmuir isotherm giving the curves shown in Figs. 4 and 5. These graphs show that the response of the sensors reduce with increased humidity. This is expected with conducting polymer sensors as the

sample and water vapour are in competition for active sites on the sensor.

It has previously been shown that the palladium gate FET follows a Langmuir isotherm where the shift in threshold voltage is given by [7]:

$$\Delta V_{T} = \Delta V_{max} \frac{\alpha \sqrt{P_{C}}}{1 + \alpha \sqrt{P_{C}}} \tag{7}$$

This equation is similar in form to that of the polyFET, where ΔV_{max} is the maximum shift in the threshold voltage, α is a constant and P_{C} is the partial pressure of the analyte.

3. Conclusion

We have studied the I–V characteristics of a polymer gate p-channel MOSFET in air containing various concentrations of ethanol and water vapour. The drain current broadly follows a simple chemical model based on a Langmuir isotherm. We believe that in the case of the polymer MOSFET, the ethanol vapour shifts the threshold voltage V_{T} of the device via a change in the work function ϕ_{ms} between the polymer and the silicon. At this stage we do not know whether the bulk part or the surface part of the work function (or both) is modulated. A useful discussion of work function modulation effects is the review article by Bergveld et al. [8]. There was also some evidence of long term drift in the drain current which needs further investigation.

References

[1] D. Blackwood, M. Josowicz, Work function and spectroscopic studies of interactions between conducting polymers and organic vapours, J. Phys. Chem. 95 (1) (1991) 493–502.
[2] S.M. Sze, Physics of Semiconductor Devices, 2nd edn., Wiley, New York, 1981, pp. 431–455.
[3] J.V. Hatfield, K.S. Chai, A conducting polymer gasFET, Proceedings EUROSENSORS XI, Warsaw, Poland, Sept. 1997, pp. 739–742.
[4] A. Garde, J. Alderman, W. Lane, Development of a pH-sensitive ISFET suitable for fabrication in a volume production environment, Sens. Actuators, B 27 (1995) 341–344.
[5] P.I. Neaves, J.V. Hatfield, A new generation of integrated electronic noses, Sens. Actuators, B 26 (1995) 223–231.
[6] G.C. Bond, Heterogeneous Catalysis: Principles and Applications, OUP (Clarendon), London and New York, 1974.
[7] I. Lundstrom, C. Svensson, A. Spetz, H. Sundgren, F. Winquist, From hydrogen sensors to olfactory images — twenty years with field-effect devices, Sens. Actuators, B 13–14 (1993) 16–23.
[8] P. Bergveld, J. Hendrikse, W. Olthuis, Theory and application of the material work function for chemical sensors based on the field effect principle, Meas. Sci. Technol. 9 (1998) 1801–1808.