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A ring oscillator based on HIFETs

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A B S T R A C T

A hygroscopic insulator field-effect transistor (HIFET) ring oscillator with three inverters was built and tested under ambient laboratory conditions. An operating voltage of −2 V was used, yielding a peak-to-peak output voltage of 1.1 V and an oscillation frequency of 28 mHz. For Spice (simulation program with integrated circuit emphasis) simulation of the HIFET circuits the measured HIFET output characteristics were fitted to a DC (direct current) model and additional measurements were made to find the magnitude of the capacitive and resistive elements in the HIFET gate structure. The results indicated that HIFETs have a good potential for use in amplifier and sensor circuit applications where high operation speed is not crucial.

1. Introduction

One of the most attractive properties of organic electronics is the possibility of using mass production methods, such as printing, to produce low-cost large-area electronic circuits and devices on flexible substrates. This requires the fabrication of high performance solution-processable polymer transistors [1]. Solution deposition of a multilayer transistor structure is challenging, especially at the active semiconductor/dielectric interface, where dissolution of the underlying layer may cause interfacial effects such as increased surface roughness which may have a disadvantageous effect on the electrical performance of the transistor [1]. The gate dielectric plays an important role in determining the properties of field-effect transistors, as the gate affects the transistor channel by means of electrostatic coupling, so that operation of the transistor at low voltages requires the use of a high permittivity dielectric or a very thin dielectric layer. Very thin polymer dielectric layers that are of high quality and free of pin-holes are difficult to fabricate by solution processing, and most polymers are of low permittivity. Hence, polymer transistors typically require high operating voltages (tens of volts).

Low-voltage operation of an organic transistor can alternatively be achieved with electrochemical transistors [2] or by using an electrolyte as a gate insulator [3,4]. Inverter and ring oscillator circuits with operation frequencies of ~10^2 Hz have been proposed for electrolyte-gated transistors [4,5]. The hygroscopic insulator field-effect transistor (HIFET) takes advantage of the fact that poly(4-vinylphenol) (PVP) is a weak electrolyte in contact with water, methanol or ethanol, and the operating principle differs from that of traditional organic field-effect transistors (OFETs) in that channel current modulation is not controlled by a pure field effect but is caused by H+ ions moving vertically in the hygroscopic insulator, where they build up opposite charge densities on the two sides of the insulator [6,7]. It has been proposed that the ions moving in the insulator may cause electrochemical oxidation and reduction of poly(3-hexylthiophene) (P3HT) at the P3HT/PVP interface, which results in modulation of the channel

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current of the transistor [6–8]. HIFETs have many advantageous properties, such as insensitivity to surface roughness [9] or insulator layer thickness [7]. A clear saturation region for transistor operation and relatively high channel current levels (a few μA's) are achievable at low operating voltages (less than 2 V). In addition, HIFETs have been fabricated completely on plastic substrates by printing methods [10]. Because of the current modulation mechanism, the internal operation of a HIFET is relatively slow [7], but there are many applications for which slow transistors are suitable, e.g. the measuring of long time intervals or use in conjunction with chemical sensors.

Effective design of organic transistor circuits requires a proper simulation model for the organic transistors. Various drain current models for OFETs have been presented, and a generic model has been developed for OFETs, which have many unique properties compared with traditional field-effect transistors (FETs) [11]. On the other hand, modified metal oxide semiconductor field-effect transistor (MOSFET) models are often used for OFETs, because of the many similarities in their characteristics [12], and the suitability of an amorphous silicon thin-film transistor (a-Si:H TFT) model [13] for organic transistors has also been demonstrated [14,15]. One advantage of the a-Si:H TFT model is that it includes gate bias-dependent mobility, which is also a typical feature of OFETs [16]. The above mentioned FET models can also be used with modified parameters for modeling the DC operation of a HIFET, because the current/voltage (I/V) characteristics of a HIFET are very similar in shape to typical field-effect transistor curves. The operating principle of a HIFET means that there is no straightforward physical basis for the model, so that the proper parameter values mainly have to be found by experimental adjustment.

We present here the operation principle and structure of a HIFET ring oscillator consisting of three inverter stages, and quote some measurement results. A physically simplified Spice model has also been developed for the simulation of HIFET circuits.

2. Experimental

A typical structure for a top-gate, bottom-contact HIFET is shown in Fig. 1a. HIFETs with two channel widths (W = 1.5 and 7.5 mm) but the same channel length (L = 25 μm) were fabricated on laboratory glass slides and subjected to ultrasonication at 60 °C in H_2O, acetone and isopropanol for 10 min each. Gold electrodes around 30 nm thick were then vacuum-evaporated onto the substrates through a shadow mask, and a roughly 50 nm thick semiconducting layer was fabricated on the substrates by spin-casting P3HT (Plextronics) from an 8 mg/ml solution in p-xylene. The samples were dried at 70 °C for 20 min before the ∼1 μm thick PVP (Sigma–Aldrich) dielectric layer was spin-cast from a 100 mg/ml solution in ethyl acetate. The chemical structures of P3HT and PVP are presented in Fig. 1b and c, respectively. Pedot:PSS (Poly(3,4-ethylenedioxythiophene):poly(styrene sulphonate)) (Baytron-P, from H.C. Starck) gate electrodes were fabricated manually after the dielectric film had dried for 30 min at 70 °C.

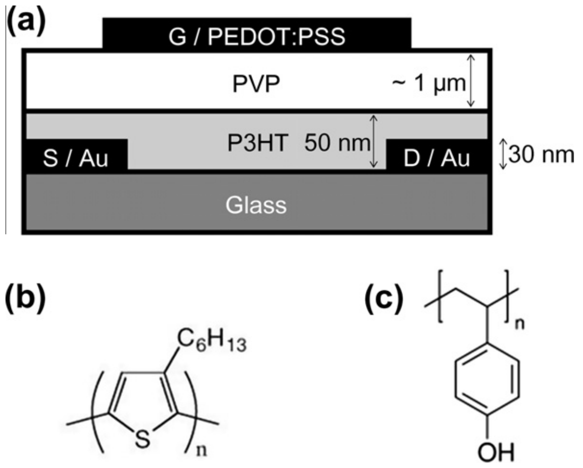

Fig. 1. (a) Schematic cross-section of a HIFET structure and the chemical structures of (b) the P3HT semiconductor and (c) the PVP insulator.

The oscillator circuit was built using PCB (printed circuit board) wiring and discrete HIFETs on glass slides that were fastened to the PCB with double-sided tape. The electrical contacts with the PCB were made with screw connectors and the wires were glued to the electrodes of the transistors with electrically conductive paint (ELEKTROLUBE® SCP). The ring oscillator was composed of three inverters (of the design presented in Fig. 2) connected in a loop. Because of the asymmetry of the voltage transfer characteristics of simple HIFET enhancement load inverters, referred to here as amplifier stages, they could not be used to drive subsequent inverters while sustaining logic integrity [17]. Consequently a level shifter was added to make the inverter characteristic more symmetrical.

The curves for the characteristics of the HIFETs and inverters were measured with a Keithley 4200-SCS semiconductor parameter analyzer using a scan speed of 0.1 Vs^{-1}. The output voltage of the oscillator and the voltages in the circuit nodes during the electrical testing

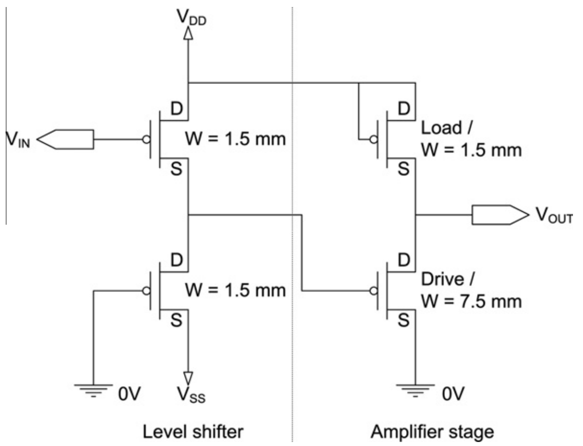

Fig. 2. Schematic diagram of the circuit of the HIFET inverter.