Fast and Sensitive Electret Polymer Characterization by Extended Floating Gate MOSFET

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ABSTRACT

A new characterization method for charge conditions in electret polymer films is proposed. This method uses the change of the threshold voltage in an EEPROM (electrically erasable and programmable read-only memory) device to evaluate the effective charge density in electret. The EEPROM device has an extended floating gate that is capacitively coupled to a sensing gate in direct contact with the electret polymer film. It also has a control gate similar to that in the conventional EEPROM device driven by test signals. By the total capacitive loads and effective charges seen on the floating gate, the surface potential of the transistor channel in the subthreshold region is a linear function of effective electret charge density. Representative measurements with several electret charging conditions, such as photo poling and mechano poling are provided. With the bandwidth of the EEPROM device typically much higher than 1 kHz, real-time charging characteristics with sub-millisecond resolution can be obtained.

Index Terms — **Electrets, EEPROM, photo poling, mechano poling, polarization, polymer, floating gate, control gate, sensing gate, threshold voltage.**

1 INTRODUCTION

MANY device applications, such as microphones, radiation dosimeters, and semiconductor carrier measurements, can have improved performance and reduced power consumption by utilizing inorganic and polymer electrets [1-4]. An electret is a dielectric material exhibiting a quasi-permanent electrostatic charge or charge dipole. The electret charge can be the combination of surface charges, space charges, and charge polarization. There are various methods for forming space-charge and dipolar electrets. For example, space-charge in electrets can be achieved by injecting carriers from discharging or particle beams. Other methods consist of carrier generation within the dielectric by light, radiation or heat with simultaneous charge separation by an electric field [1]. On the other hand, dipolar electrets can be often obtained by application of a high electric field at room temperature [5, 6]. This experimental work presents a new characterization method of the polymer electret by the EEPROM (Electrically Erasable Programmable Read Only Memory) device with an extended floating gate. The charges in the polymer film are capacitively coupled to the floating gate, in the same manner of the conventional control gate directly driven by biases [7, 8]. The polymer film sits on a sensing gate electrically isolated from the floating gate by a dielectric. The net charge density in the polymer film weighted by the distance to the sensing gate will influence the potential on the floating gate. Accordingly, the threshold voltage of the EEPROM device at the control gate will change and can be correlated to the electret charge density.

The EEPROM structure is at present the most dominant nonvolatile memory device in microelectronics with an estimated market size of $>$ US $\$10^{10}$ each year and forecast of strong growth for at least 10-15 years [9]. Figure 1 shows a basic EEPROM structure with n-type source and drain. The device is similar to a traditional MOSFET except that an extra electrically floating conductor layer is sandwiched between the control gate and the channel. The static charge stored in the floating gate has over 10-year lifetime and will influence the threshold voltage of the MOSFET channel, which is used to distinguish the stored binary information.

Programming can be implemented by several possible mechanisms [9]. As an example, the channel hot carrier injection is illustrated in Figure 1, which is performed by applying a high voltage on the control gate (usually around 12V) and drain ($\sim$ 6 V) terminals with a grounded source. The substrate is often grounded or further reverse biased to enhance the injection efficiency [10]. During hot-carrier

Manuscript received on 19 May 2004, in final form 3 May 2005.

 1070-9878/05/$20.00 © 2005 IEEE

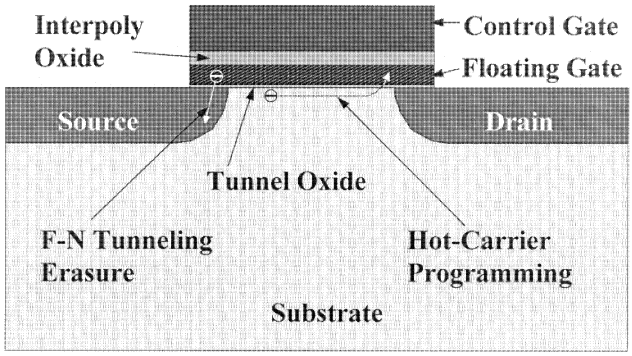

Figure 1. The cross section of an EEPROM device.

injection, electrons with enough kinetic energy to overcome the oxide energy barrier will be trapped at the floating gate. After removing the programming voltages, the trapped negative charges will delay channel inversion, which translates into an effective increase in the MOSFET threshold voltage. To turn on the device during the read operation, a higher control gate voltage is needed to overcome the effect of the floating-gate charges. The erasure operation is performed with the gate grounded and the source at a high voltage, typically also around 12 V, when the electrons in the floating gate will leak out through the Fowler-Norhdeim (F-N) tunneling mechanism [9]. Different areas of the gate oxide are used for programming and erasure in this illustration.

In this paper, we use an EEPROM device to monitor the threshold voltage, which is influenced by the effective charges in the electret polymer film. Figure 2 shows the characterization device structure. The device is fabricated through the MOSIS foundry [11] with a 2-polysilicon and 2-metal process. Results for different poling methods are shown for devices with different sensing gate areas. Due to the fast and sensitive extraction, real-time monitoring of poling characteristics can be obtained.

2 THEORY

Figure 3 illustrates a capacitor-divider model [7, 8] for the EEPROM device. The floating gate is connected with many input nodes through different dielectric layers, which is the same as the parallel connection of capacitors from the nodes shown in Figure 3. The net charge in the floating gate is the sum of the charge in each capacitor. V_{FG} is the floating-gate potential. V_{CG}, V_D, V_B, and V_S are the input signal voltages of control-gate, drain, substrate, and source, respectively. V_E is effective potential on the sensing gate set by the polymer electret film. C_{CG}, C_S, C_D, C_B, and C_E are the capacitive coupling coefficients between the floating gate and each of the input nodes. Let Q_{FG} denote the net charge in the floating gate,

$$Q_{FG} = C_{CG}(V_{FG}-V_{CG}) + C_E(V_{FG}-V_E) + C_D(V_{FG}-V_D) + C_B(V_{FG}-V_B) + C_S(V_{FG}-V_S) \quad (1)$$

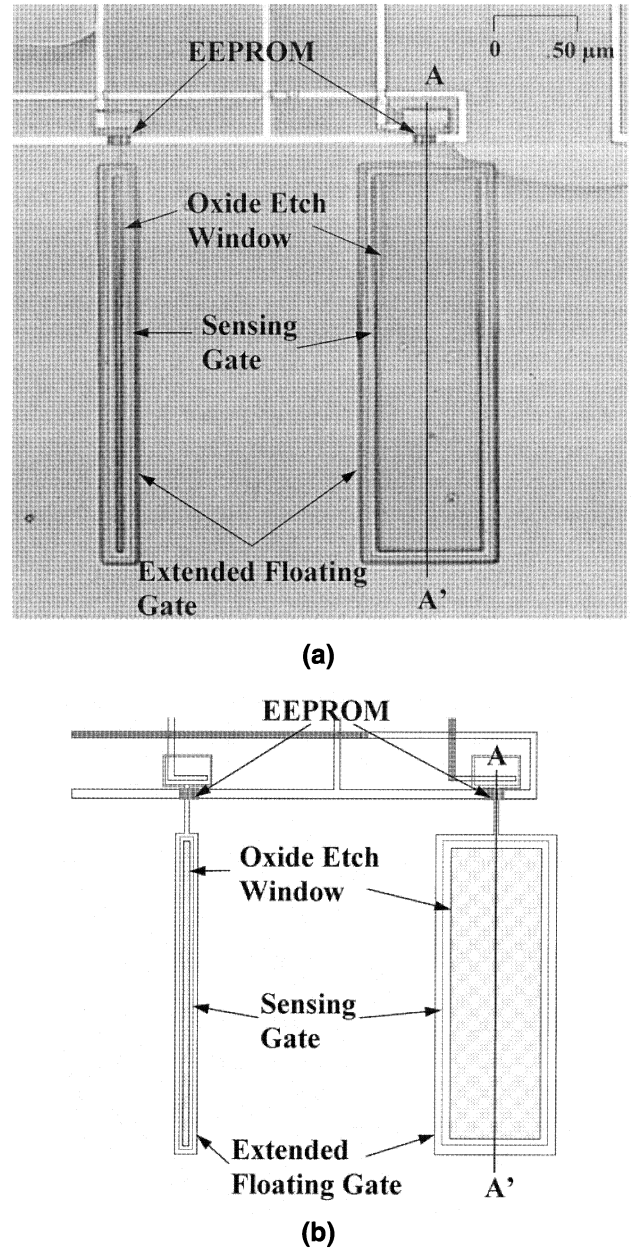

Figure 2. The sample for polymer electret characterization. a, layout; b, micrograph.

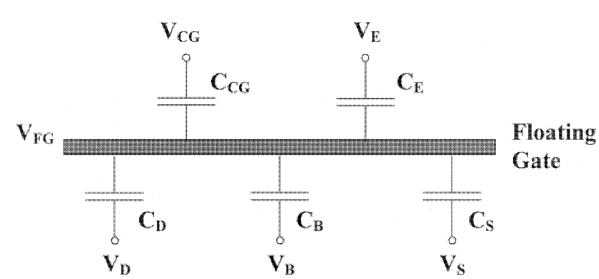

Figure 3. The capacitive-divider model for the EEPROM device.

If we assume that no charge injection occurs during IV measurements, then Q_{FG} is equal to the initial charge on the floating gate, which we will take as zero at the mo-

ment for simplicity. If voltages are measured with respect to the grounded substrate with the source and the substrate being shorted, equation (1) reduces to

$$V_{FG} = \frac{C_{CG}V_{CG} + C_E V_E + C_D V_D}{C_{TOTAL}} \tag{2}$$

where

$$C_{TOTAL} = C_{CG} + C_E + C_D + C_B + C_S \tag{3}$$

We will denote V_{FG_TH} and V_{CG_TH} as the threshold voltages of the EEPROM seen from the floating gate and the control gate, respectively. The EEPROM turns on at the condition of $V_{FG} > V_{FG_TH}$, namely

$$\frac{C_{CG}V_{CG} + C_E V_E + C_D V_D}{C_{TOTAL}} > V_{FG_TH}. \tag{4}$$

Equation (4) is rearranged for V_{CG} as

$$V_{CG} > \frac{C_{TOTAL}}{C_{CG}} V_{FG_TH} - \frac{C_E}{C_{CG}} V_E - \frac{C_D}{C_{CG}} V_D \tag{5}$$

Before poling, there is no effective charge in the polymer film. Thus, the initial $V^i_{CG_TH}$ is given by

$$V^i_{CG_TH} = \frac{C_{TOTAL}}{C_{CG}} V_{FG_TH} - \frac{C_D}{C_{CG}} V_D. \tag{6}$$

After poling, charges are injected to the polymer film or dipoles in the film are polarized. If Q_E is the total effective charges seen at the surface of the sensing gate, according to the Poisson equation, it will affect the potential of the floating gate by the capacitive coupling [12]. Therefore, V_{FG_TH} in equation (6) shifts to $V_{FG_TH} - Q_E / C_{TOTAL}$ after poling. Correspondingly, $V^i_{CG_TH}$ shifts to $V^f_{CG_TH}$ as

$$\begin{aligned} V^f_{CG_TH} &= \frac{C_{TOTAL}}{C_{CG}} \left(V_{FG_TH} - \frac{Q_E}{C_{TOTAL}} \right) - \frac{C_D}{C_{CG}} V_D \\ &= \frac{C_{TOTAL}}{C_{CG}} V_{FG_TH} - \frac{Q_E}{C_{CG}} - \frac{C_D}{C_{CG}} V_D \end{aligned} \tag{7}$$

The effective charge density ρ_E in coul/cm^2 of the electret film can be obtained from (6) subtracted by equation (7)

$$\rho_E = Q_E / A_{SG} = -\Delta V_{CG_TH} C_{CG} / A_{SG} \tag{8}$$

where A_{SG} is the area of the sensing gate.

3 EXPERIMENTAL ELECTRET POLYMER CHARACTERIZATION

3.1 POSTPROCESSING PROCEDURES

Our EEPROM devices have n-type sources and drains with large extended floating gates, which are specially designed to provide amplified capacitive coupling to the sensing gate. The oxide etch window as a post-processing step is applied to remove the passivation layer on top of the sensing gate. Two different extended gate areas are employed to decouple the parasitic elements. The large sensing gate has an area of 28,800 μm^2, which is ten times larger than the small one. The illustrative cross-section of line AA' in Figure 2 is shown in Figure 4.

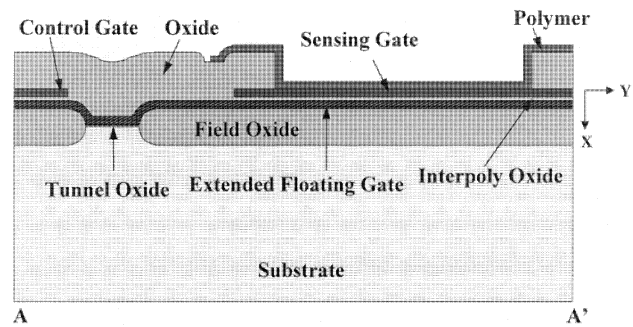

Figure 4. The cross-section schematic of the EEPROM device shown in Figure 2.

Post-processing of polymer coating can be done either by direct attachment from pre-made solid polymer films or by dip-coating from polymer solutions. We will only present the results by dip-coating here. The Teflon AF (amorphous fluoropolymer) solution is 400S, provided by DuPont [13]. The drying step is by a hot plate at 130°C to evaporate the FC75 solvent from 3M. The Teflon film thickness is measured by a profilometer at 60 nm.

3.2 CHARGING METHODS

The first electret charging method illustrated here is photo poling by UV light with high dc biases. We used UV lamps producing 8 W of one of the 254/302/365 nm wavelengths, which is located near the sample on a probe station. A plate probe of high voltage during the photo poling is located directly on the polymer film surface and the ground is connected to the substrate. This setup will put a large electric field across the electret polymer film. Further UV illumination will excite electrons and holes in the insulating polymer film traveling in opposite directions by the applied electric field. Some carriers can go out of the external surfaces of the polymer film and the others can be trapped to form space charge [14]. We have verified the effect of UV irradiation by applying transparent ITO (Indium-tin Oxide) contacts on the electret film, and found that the electric field uniformity is not a critical factor in photo poling. Dipole polarization can also result from different electron and hole transport properties. Photoelectret equilibrium charge density is mainly governed by the polarizing field intensity, which can be estimated by the product of light intensity and time of polarizing [15]. The samples are erased by 254 nm UV light of 1.6 W for an hour without applied electric fields before all poling tests, which serves as the reference in obtaining threshold voltage difference.

The second poling method is mechano-poling by applying mechanical pressure on Teflon AF that has gone through photo-poling. The original amorphous Teflon is not piezoelectric due to lack of long-range directional order of charge density. However, if Teflon already contains significant space charges, it will demonstrate pressure responses from mechanical strain [16]. For the same characterization structure, a mechanical pressure effect can be accurately determined, which may be used as a charge-based pressure sensor. We will illustrate the sensitivity and bandwidth of mechanical pressure measurements from the proposed structure.

4 RESULTS AND DISCUSSIONS

The results from representative tests with different poling conditions are given below, which shows the range and sensitivity of our characterization method. Size difference of the extended gate area is used to de-embed the intrinsic parasitic elements and to obtain a larger range of effective electret charge per unit area.

4.1 DIFFERENT EXTENDED GATE AREAS

Figure 5 shows the typical threshold voltage characteristics of two EEPROMs with 302 nm UV and 200 V poling voltage. With the same charge density in the polymer film, ΔV_{CG_TH} with the larger sensing gate area is bigger according to equation (8). However, ΔV_{CG_TH} is not exactly proportional to the ratio of the extended gate areas because the small extended gate area has relatively large parasitic capacitance. ΔV_{CG_TH} of the two EEPROMs under test are −6.0 V and −0.10 V. C_{CG}, a capacitance between the floating gate and the control gate is 0.368 pF. Thus, the charge densities ρ_E are 7.66×10^{-9} C/cm^2 and 1.27×10^{-10} C/cm^2 of positive charges for the large and small sensing gates, respectively. The difference in charge density can be explained by the UV shadowing and film thickness variation in the smaller sensing gate. The anomalous high current in the deep subthreshold region ($V_{CG} < 1.0$ V) in the small sensing gate case is repeatable

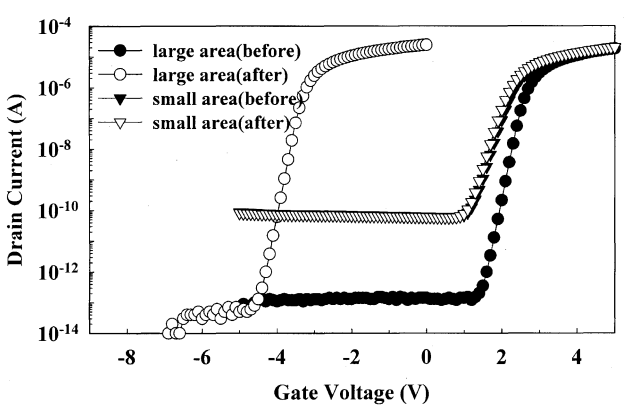

Figure 5. The threshold voltage characteristics with different sensing gate areas of the EEPROM devices. The poling condition is 200 V biasing and 302 nm UV irradiation for an hour.

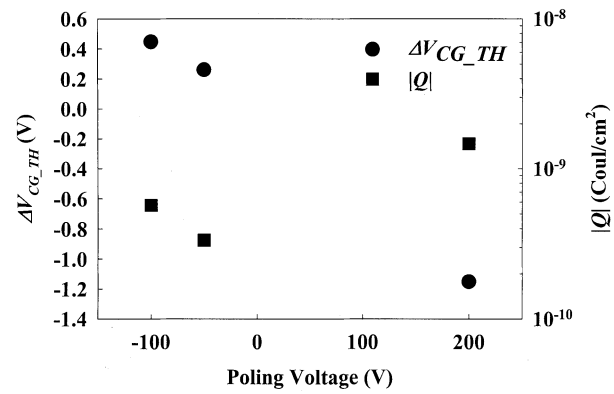

Figure 6. The threshold voltages and the effective charge density in the polymer film with different poling biases.

and does not appear before the Teflon coating. The physical origin of this anomalous subthreshold current is not clear and needs further investigation.

4.2 DIFFERENT POLING BIASES

Figure 6 shows the threshold voltage characteristics of the EEPROM device with different poling voltages, −50, −100 and 200 V. The changes of the threshold voltage are 0.448, 0.262, and −1.152 V, respectively, which correspond to the charge densities ρ_E in the polymer film as -5.72×10^{-10}, -3.35×10^{-10} and 1.47×10^{-9} C/cm^2 respectively. The polarity and magnitude of the extracted charge density under different poling biases agree well with the expected values of the Teflon AF [2].

Figure 7 shows the time characteristics of ΔV_{CG_TH} with different poling biases. For 200 V poling condition, the shift of the threshold voltage is saturated after 15 minutes poling application. For -50 and -100 V, ΔV_{CG_TH} saturates in 2-3 minutes. The effective charge density will saturate because the electric field within the electret film will decrease with the generation of static charges or charge dipoles during the poling process.

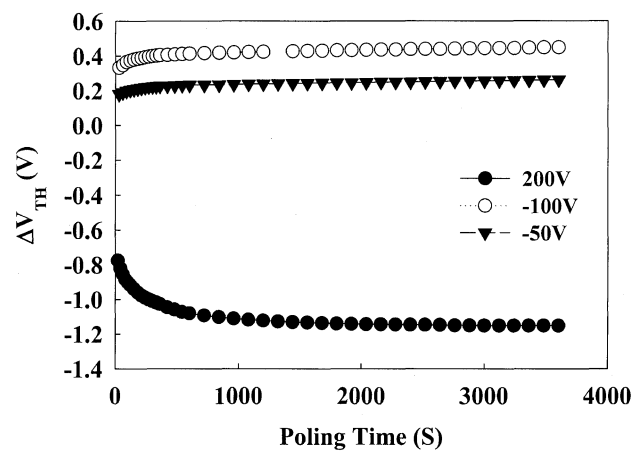

Figure 7. Real-time monitoring of the threshold voltages during charging with different poling biases.

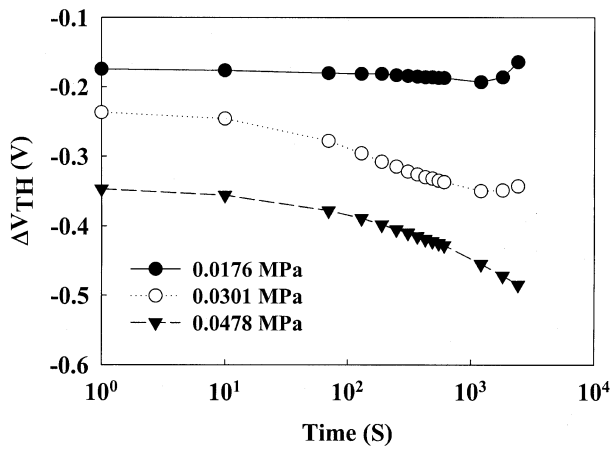

Figure 8. The threshold voltage characteristics of the EEPROM device under mechanical pressure of 0.0176, 0.0301 and 0.0478 MPa.

4.3 THE MECHANICAL PRESSURE EFFECT

Figure 8 illustrates the measurements of the pressure effect. After UV erasure for reset and repeated charge injection by photo poling, the Teflon AF on the sensing gate is subject to mechanical pressure. The originally non-polar Teflon AF film will be polarized after the photo poling process with residual charges, which will continuously change with further mechanical strain. Figure 8 shows the time characteristics of ΔV_{CG_TH} when pressure is applied to the Teflon AF film after the photo poling procedure. Although the initial response is instantaneous, there is a long-term drift that is either due to viscoelastic deformation or residual charges moving to the closest surface.

From Figure 8 and equation (8), the changes of the threshold voltage of each pressure are -0.176, -0.246 and -0.356 V after 10 minutes of applied pressure. The effective charge densities are 2.25×10^{-10}, 3.14×10^{-10} and 4.55×10^{-10} C/cm^2 of positive charges for 0.0176, 0.0301 and 0.0478 MPa, respectively.

5 CONCLUSION

A new characterization of the electret polymer film with an extended floating gate of an EEPROM has been demonstrated. The charges injected and/or polarized in the electret polymer film can be directly obtained from the change of the threshold voltage. Due to the direct CMOS integration and sensitive response with very short settling time (less than 1ms), the proposed structure can be effectively applied to real-time monitoring electret charging and mechanical pressure effect.

ACKNOWLEDGEMENTS

This work is supported by the ECS Division of National Science Foundation (NSF). The authors would like to thank the fruitful discussions with Dr. Zengtao Liu of Micron Technologies.

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