Engineering Ferroelectric Polymer Memories: Confounding Factors Which Obscure Polarization

Vasileia Georgiou[ab], Dmitry Veksler[a], Jason P. Campbell[a], Jason T. Ryan[a], Dimitris E. Ioannou[b], and Kin P. Cheung[a]

[a] National Institute of Standards and Technology, 100 Bureau Drive, MS 8120, Gaithersburg, Maryland 20899, United States,

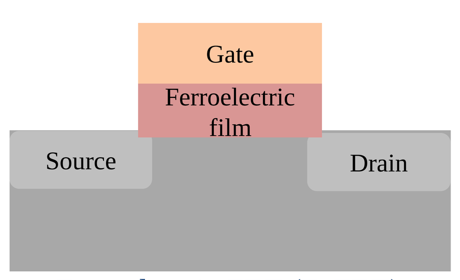
[b] Department of Electrical and Computer Engineering, George Mason University, 4400 University Drive, Fairfax, Virginia 22030, United States.

Abstract

When studying Ferroelectric Memory cells, careful analysis of the direction of the hysteresis, dependence of the hysteresis on the gate voltage ramp rate, the thickness of the polymer insulating layer, the symmetry of the hysteresis curves and their dependence on the amplitude of the gate voltage can greatly aid in deconvolving complicated FeFET (Ferroelectric Field Effect Transistor) hysteresis.

Properties of FeFET memory cells based on polar polymers

- **Thermal budget**
- **Scaling**
- **Wide range of applications:** flexible electronics, high performance, low power, cryogenic, etc.

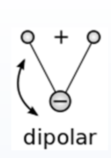


Ferroelectric FET (FeFET)

- **Non-destructive READ operation**
- **Memory mechanism**: by observation of the hysteresis in Id-Vg characteristics

Hysteresis Mechanisms

- **Polarization of the Dielectric** (desired mechanism)

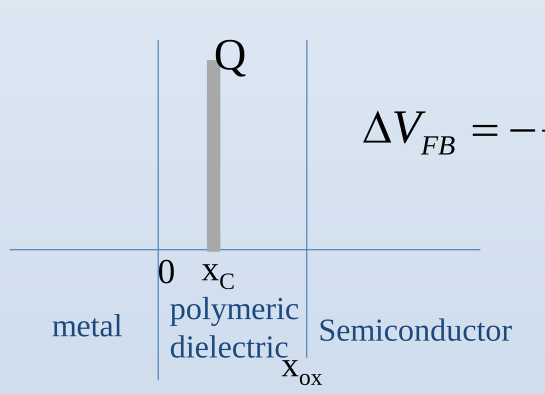


- Charge Trapping
- Motion of Mobile Ions in the polymeric dielectric

Despite many studies over the last decades[1,2] –
No unambiguous proof of the FE polymer memory effect

Effect of Charge stored in the polymer layer

Distribution of charge in the dielectric affects V_{FB} shift:



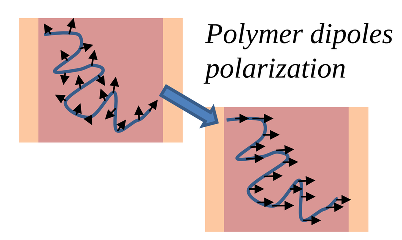
$$\Delta V_{FB} = -\frac{1}{C_{ox}}\int_0^{x_{ox}} \frac{x}{x_{ox}}\rho(x)dx = -\frac{Qx_C}{\varepsilon A}$$

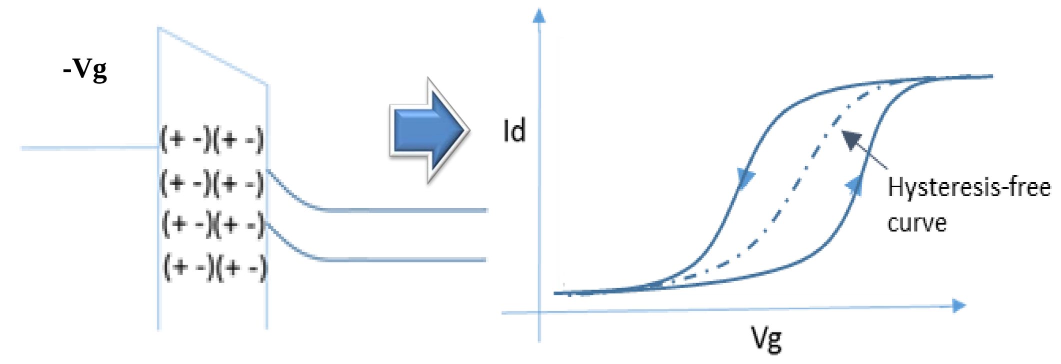
The closer the charge centroid to the semiconductor/dielectric interface, the more it affects V_{FB} shift.

→ In thick polymers, the charge located in the vicinity of the metal/dielectric interface has minimal effect on ΔV_{FB}.

Ferroelectric Polarization

- The dipoles in the polar polymer align with the field by rotation.
- The rate of dipole rotation depends on the polymer, the temperature and the applied field.
- Hysteresis is observed when dipoles **partially** follow the field.

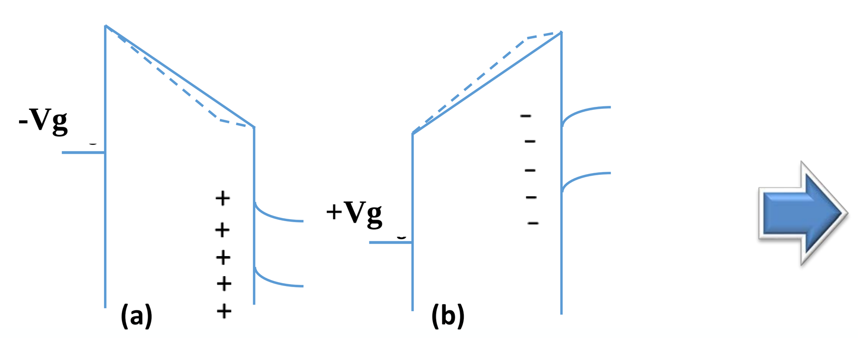


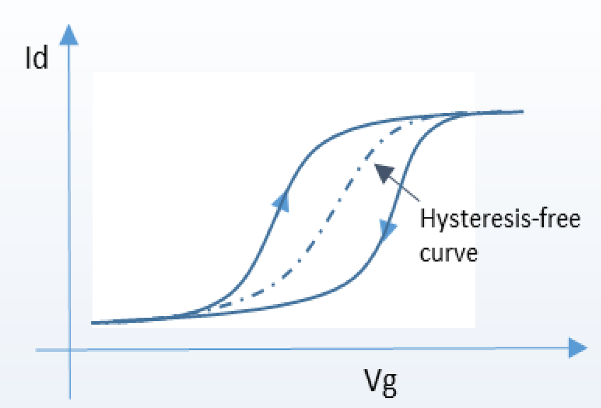


A counter-clockwise hysteresis loop, nearly symmetrical around the ideal Id-Vg characteristic

Charge-trapping

Charge injection from the substrate:





A hysteresis loop, nearly symmetrical around the ideal Id-Vg characteristic.

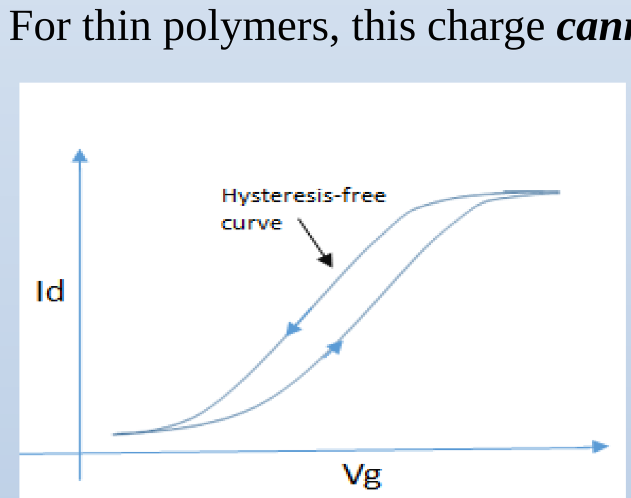
Charge injection from the gate:

- For thick polymers with low leakage current, charge injection from the gate can be ignored, since the tunneling depth is a logarithmic function of available time for injection:

$$t = t_0 e^{2x\sqrt{2m\varphi/\hbar^2}}$$

Consider, for example, that for SiO_2 tunneling depth for realistic measurement time is less than 10 nm from injecting interface → insignificant effect on V_{FB} when using *μm-order* thick polymer.

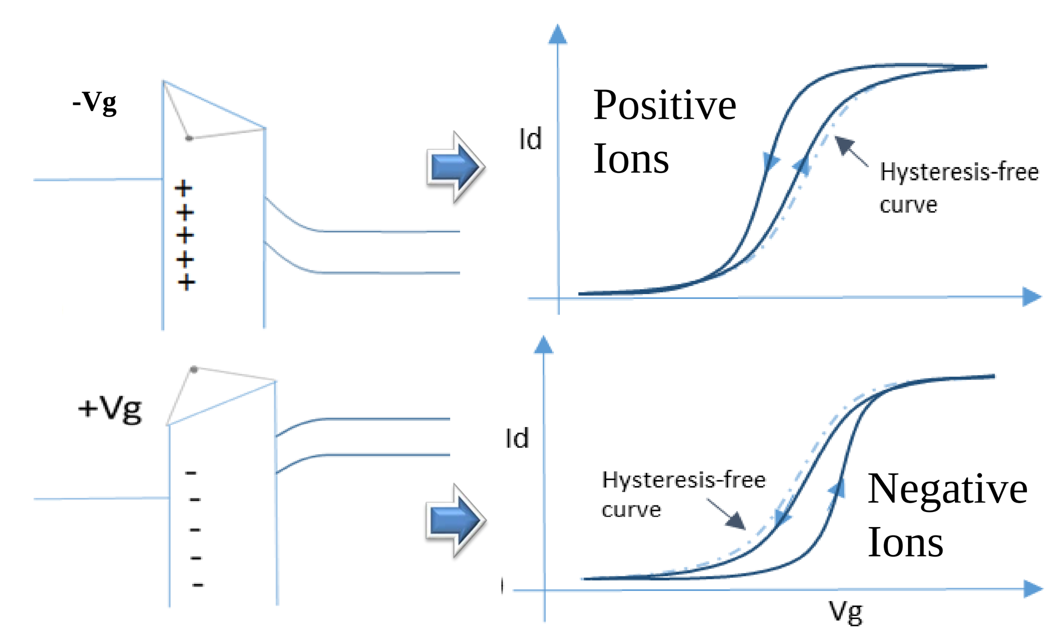
- For thin polymers, this charge ***cannot*** be ignored.



Only electrons are injected from gate→ the hysteresis loop stays entirely on the r.h.s. of the charge-free curve.

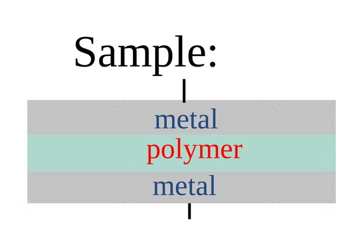
Mobile Ions in the Polymer

- Mobile ions can affect V_{FB} even at room an lower temperature.
- V_{FB} shift caused by mobile ions is unidirectional. The hysteresis loop is counter-clockwise and is asymmetrical.



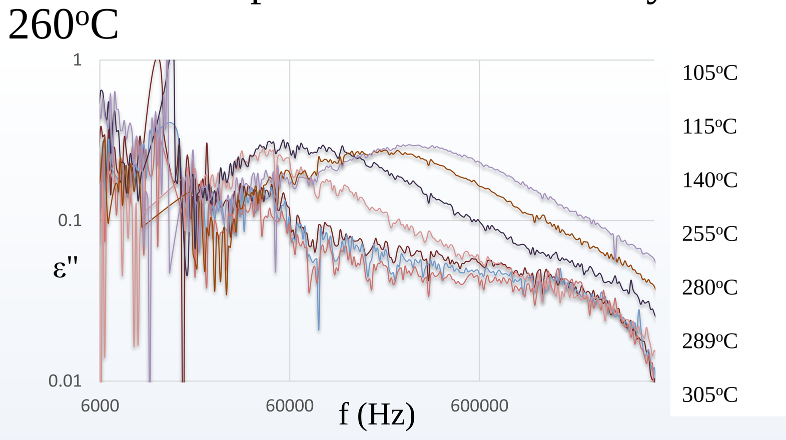
Experimental Results

Polar polymer with high T_g



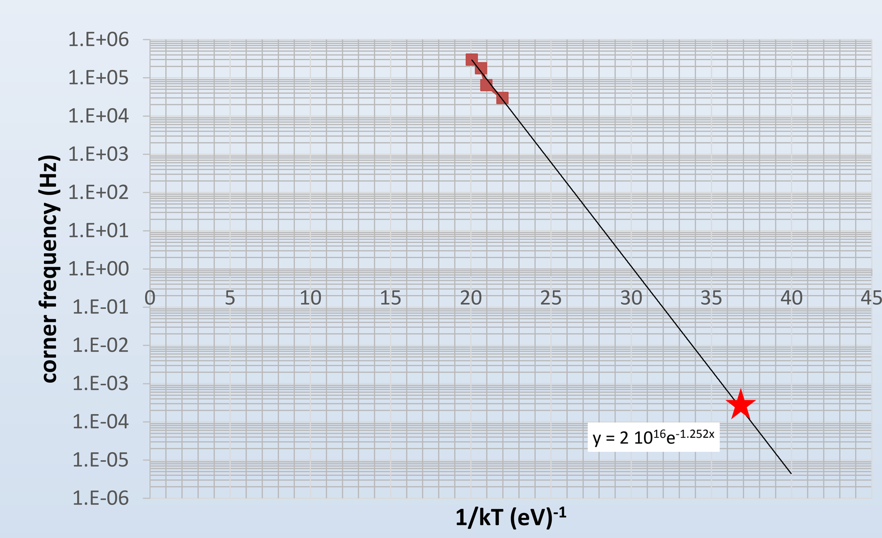
Polymer used: CP1, with Tg = 260°C

- The polymer can be poled (performing write/erase) at temperatures close and above T_g, when dipoles can rotate quickly.
- At T << T_g, dipoles are locked in position and can hardly rotate.



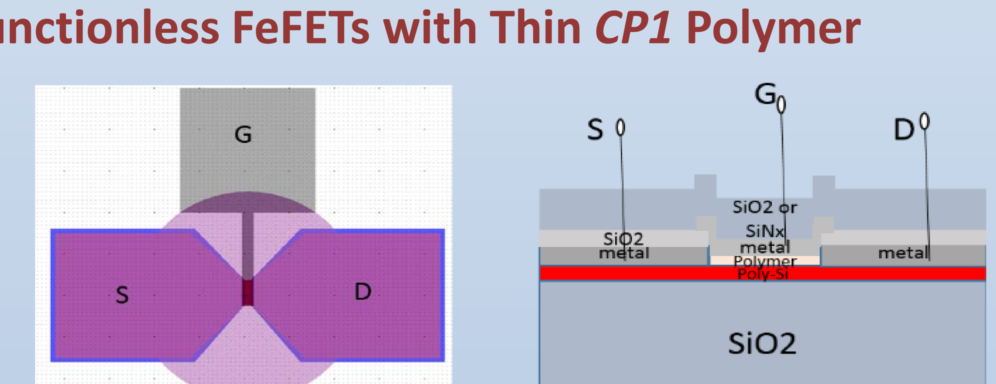
Peaks in ε'' spectra correspond to corner frequencies at which dipoles are not anymore able to follow the applied field.

Predicted rotation speed of the dipoles at RT



No ferroelectric effect could be observed at RT at frequencies > 1mHz.

Junctionless FeFETs with Thin *CP1* Polymer

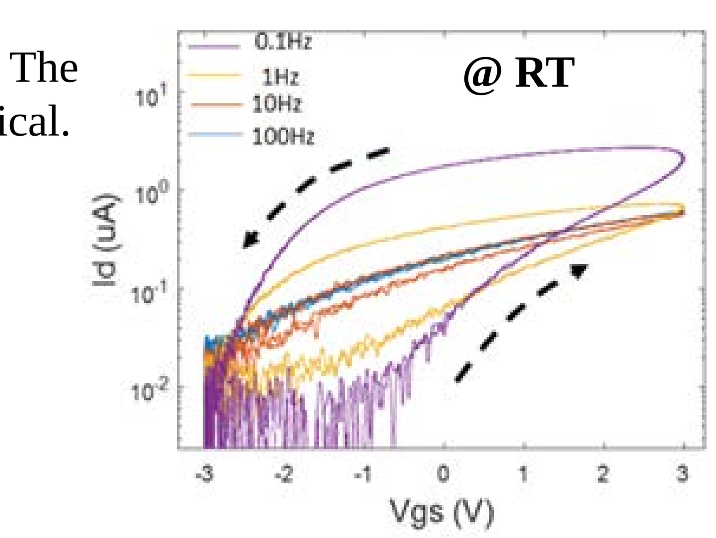


Device top view

Device cross-section

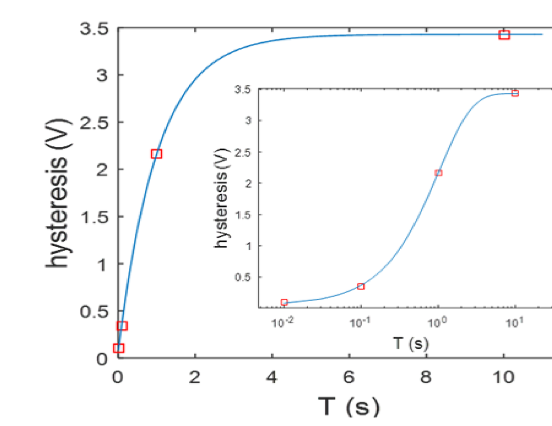
Experimental Results (cont.)

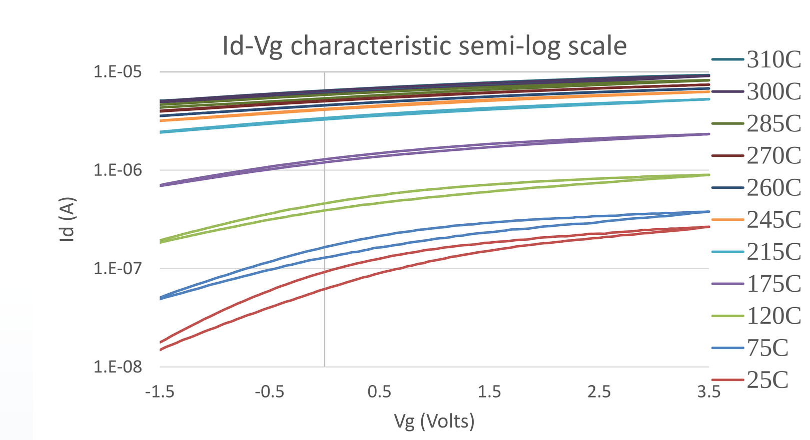
Hysteresis Observations

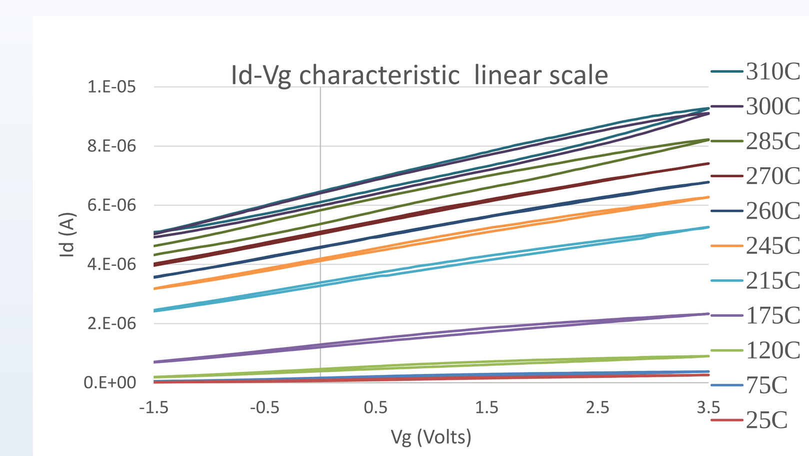


- No ferroelectric effect at RT
- Charge-trapping from the substrate side ruled out due to the hysteresis loop direction
- At 100Hz, no hysteresis observed.
- *f* > 10 Hz, charge injection from gate side is present
- Bellow 10Hz, sweep is slow enough that positive mobile ions start to produce their own hysteresis.

- Electron tunneling dominates at shorter periods.
- Rapid increase and then the saturation at longer periods is consistent with mobile ions and their reaching of the substrate interface.







Hysteresis decreases with temperature and eventually disappears just before T_g. Then appears again and starts increasing, indicating that another mechanism (Ferroelectric effect) dominates at high temperatures.

Conclusions

- Thick polymers (90% of current literature): hysteresis loop direction, position, and symmetry can reveal the dominant hysteresis mechanism.
- Thin polymers (more technologically relevant): analysis is more complicated, but it is possible to differentiate the mechanisms.

References

1. R. C. G. Naber et al., "High-performance solution-processed polymer ferroelectric field-effect transistors", nature materials, 4, 243 (2005).
2. C. A. Lee, et al., "Hysteresis mechanism and reduction method in the bottom-contact pentacene thin-film transistors with cross-linked poly(vinyl alcohol) gate insulator", Appl. Phys. Lett., vol. 88, no. 25, 252102 (2006).

Contact Information

* Kin (Charles) Cheung, kin.Cheung@nist.gov