Glassy-Electret Random Access Memory – A naturally Nanoscale Memory Concept

Vasileia Georgiou[1,2], Jason P. Campbell[1], Pragya R. Shrestha[1,3], Dimitris E. Ioannou[2], and Kin P. Cheung[1]*
1.National Institute of Standards and Technology, Gaithersburg, USA
2.Department of Electrical and Computer Engineering, George Mason University, United States.
3.Theiss Research, La Jolla, California, United States. * E-mail: kin.cheung@nist.gov

The self-heating effect (SHE) is a growing problem for decananometer CMOS and beyond with substantial efforts dedicated to mitigation. Here, we present a new memory concept which instead requires SHE exacerbation. As such, this memory concept is naturally suitable for extreme scaling. Preliminary result of this memory concept is demonstrated with an external heater as the SHE surrogates.

This memory is based on glassy-electrets. Glassy-electrets are poled polymers with glass-transition temperature, T_g, well above the operation temperature. When used as a ferroelectric memory device, the glassy-electret polymer is rapidly poled (programmed) at temperatures well above T_g (a fully molten polymer switching time < 1 ps). Upon cooling, the polarization (memory state) is "frozen" and has long retention and disturb immunity.

The Glassy-Electret Random Access Memory (GeRAM) shown in fig. 1 is a ferroelectric field-effect transistor (FeFET) memory with the ferroelectric gate dielectric replaced by glassy-electret. This key difference eliminates known FeFET problems [1, 2] such as depolarization, imprint, disturbs, etc., and adds multi-state capability and low voltage operation.

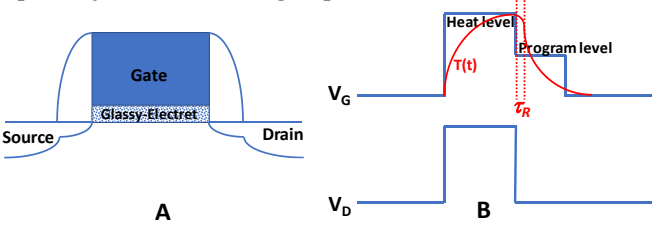

Fig. 1, A: GeRAM with Glassy-Electret as gate dielectric of a MOSFET; B: Programming pulse waveform. T(t): temperature profile; τ_R: dipole rotation time.

GeRAM programming involves the application of an electric field across the gate dielectric (polarization) while the device is held at a higher temperature (above Tg). This high temperature is provided by the SHE of the transistor. Instead of engineering the transistor to minimize SHE, one would enhance SHE by minimizing heat loss, very similar to the efforts being made in Phase-Change Memory (PCRAM) development [3]. SHE temperature increases (ΔT) of >100 C have been reported [4, 5] in the channel. With the appropriate thermal barrier engineering, it is entirely reasonable to expect ΔT extending up to 300 C.

The required ΔT is a function of the chosen polymer material. The material should ideally support <100 ps program time and >10 years retention time. This corresponds to a dipole rotation rate that varies ~19 orders of magnitude between the program and operation temperatures. Fortunately, there are existing polymers which almost meet these specifications. Fig. 2 shows the peak response frequency extracted from dielectric spectroscopy for four polar polymers plotted against temperature.

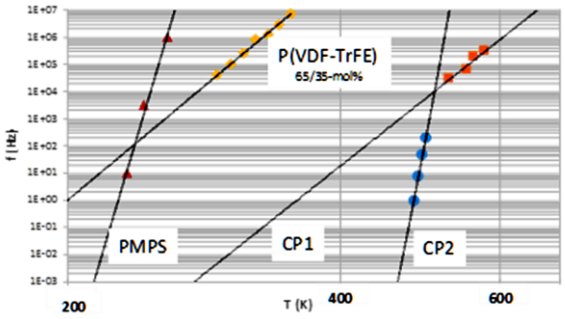

Fig. 2 Peak respond frequency as a function of temperature for 4 polar polymers. CP1 (2,2-bis(3-aminophenyl)hexafluoropropane +2,2-bis[4-(4-aminophenoxy)phenyl] hexafluoropropane) was measured in this work while the other three are extracted from literature [6-8].

The slopes for PMPS and CP2 are 5.1 C/dec and 6.5 C/dec respectively, meaning that PMPS needs ΔT=96.9 C to span 19 orders of magnitude and CP2 needs ΔT=123.5 C. The extrapolation over 19 orders of magnitude using limited range data is of course quite risky. However, at least one report exists showing the viscosity of chalcogenide glass varies smoothly as a function of temperature over 17 orders of magnitude [9]. Indeed, the trend is not quite a straight line in the log-log scale so that the straight-line extrapolation is on the pessimistic side.

T_g for CP2 is ~200 C and 100 ps program time requires ~265 C. Thus, GeRAM utilzing CP2 as the gate dielectric needs ΔT to be ~240 C. Therefore, at an operation temperature of 70 C, the retention time exceeds 10^{20}s.

Assuming the minimum heat pulse duration equals the program time, one can estimate the energy required for programming. Compared to PCRAM, where the

temperature is higher and the duration is much longer, one can see that GeRAM is intrinsically more energy efficient, by as much as 3 orders of magnitude. The steep slope of the frequency vs. temperature curve also eliminates program disturb. Decreasing the energy by half decreases the ΔT by half, leading to $>10^{18}$ times slower response.

As a proof of concept, we fabricated a GeRAM using 2 x 2 μm^2 polysilicon junction-less thin-film transistors (Fig. 3). Since this is not a high-performance nanoscale MOSFET, it cannot provide adequate SHE. Therefore, a hot-chuck provides the needed temperature gradient, but the speed is much slower (~60 s instead of 100 ps).

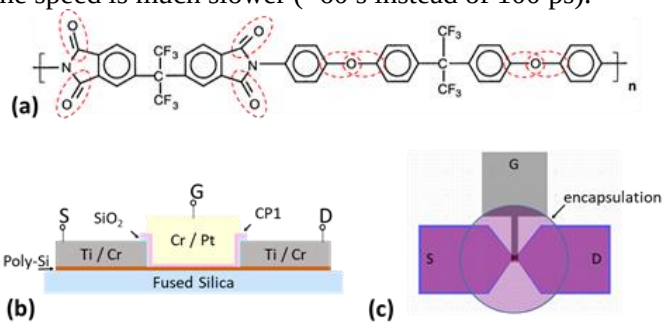

Fig. 3 (a) CP1 polymer; (b) cross section of the GeRAM fabricated; (c) top view of the GeRAM fabricated.

The junction-less TFT has, admittedly poor, gate modulation < one order of magnitude. We did not optimize the TFT as it was only needed to sense the polarization change. This is an obvious area for improvement in future fabrication cycles. Instead of the optimal CP2, the TFT's were fabricated with CP1 polymer gate dielectrics (13 nm). CP1 was chosen due to its commercially availability.

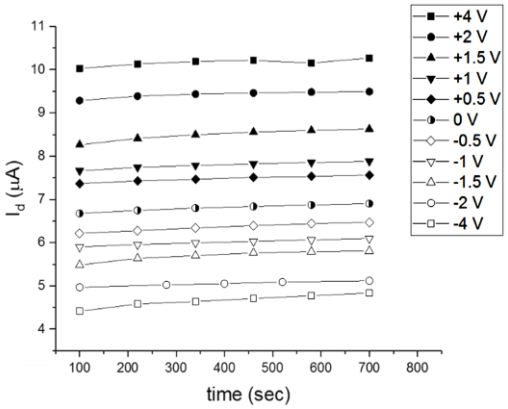

Fig. 4 Multi-states programming of the fabricated GeRAM. Program was performed at 275 C. Measurement was done at room temperature.

Fig. 4 shows programming results for various program voltages. Programming was done at 275 C and sense measurements were done at room temperature. In between each programming, the device was erased by keeping it at 275 C for 60 s with no applied voltage. 275 C is 15 C above T_g for CP1, so 60 s is sufficient to randomize the dipoles.

When the dipoles are free to rotate, programming is accomplished at any applied field and the net dipole moment will satisfy the applied field. This enables multi-states programming, as shown in fig. 4. More importantly, the programed states are immune to room temperature application of 4 V gate voltage (both positive or negative), for 10 minutes. This illustrates the robustness of GeRAM.

The remaining question lies in the endurance of the cell. If each program step heats the polymer to near melting (way above T_g) to achieve high program speed, how many times can it be programmed? Naturally, it depends on the material properties of the polymer. Many polymers remain stable in a molten state for days or longer in the absence of oxygen (or an oxidizing agent). It is expected the GeRAM will be fully encapsulated eliminating oxidation concerns. Realization of 100 ps program times, translates one day to ~10^{15} cycles.

Since the polymer is nearly melted during each cycle, full relaxation is insured for each cycle. Thus, imprint problems should not be a concern for GeRAM.

How far can GeRAM scale? Polar polymers with dipole spacing down to 0.6 nm exists. Thus a 3 x 3 x 3 nm^3 gate dielectric can contain up to 125 dipoles – sufficient for reliable operation.

Finally, the question of processing must be addressed. The need to withstand 400 C for 30 min. may prohibit lower T_g polymers even if there are energy advantages. CP1 was held at 310 C in air for nearly two hours with no problems. Thus, we expect it to be stable at 400 C for 30 min after full encapsulation. An advantage of polar polymer is the flexibility of tuning the property through synthesis – once the desired property is known.

In summary, a new memory concept is proposed. It is well suited for extreme scaling and leverages the SHE of decananometer transistors. It has the potential for very high-speed operation, and for long retention and high endurance. The potential for high-density is also very promising.

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