**I. INTRODUCTION**

In magnetic random access memory (MRAM) technology write units are typically based on spin-torque or spin-orbit torque, while read operations are based on the magnetoresistance of magnetic tunnel junctions (MTJ). But there is increasing interest in voltage-driven units due to the potential for low power operation, both active and stand-by based on different types of magnetoelectric phenomena [1–20].

The central result of this paper is an equivalent circuit model (Fig. 1) applicable to a range of magnetoelectric (ME) phenomena including both write and read operations. It consists of a capacitor circuit which incorporates the back voltage from the magnetoelectric coupling described by (1):

\[
V_{IN} = \frac{Q}{C_L} + \frac{Q}{C} + \frac{\partial E_m}{\partial Q} \tag{1}
\]

where \(E_m\) is the magnetic energy including the part controlled by the charge \(Q\) on an adjacent capacitor \(C\), through the ME effect. Equation (1) is solved self-consistently with the stochastic Landau-Lifshitz-Gilbert (s-LLG) equation which feels an effective field \(\vec{H}_{me} = -\nabla m E_m/(M_s Vol.)\), \(\nabla_m\) represents the gradient operator with respect to magnetization directions \(\vec{m}\), \(M_s\) is the saturation magnetization and Vol. is the volume of the magnet. The s-LLG treatment for all simulations in this paper is similar to what is described in [21–23] and is not repeated here. We first benchmark this equivalent circuit against the recently demonstrated MELRAM device [24, 25] which uses the magnetoelectric effect (ME) and its inverse (IME) for write and read operations. We then argue that, unlike MELRAM, the “1” and the “0” states need not be represented by states with a net magnetization. One could instead switch the easy axis, through the change in the anisotropy energy \(E_A\) by the write voltage and this change in the easy axis is detected directly as a change in the output voltage across a series capacitor through the inverse effect, allowing a “field-free” operation without any symmetry breaking magnetic field.

**II. EXPERIMENTAL BENCHMARK**

We start with the MELRAM device (Fig. 2b) reported recently in [25] where the magnetic energy has the form

\[
E_m = v_M Q (m_x^2 - m_y^2) - E_A m_x m_y + E_H / \sqrt{2} (m_x - m_y) \tag{2}
\]

The first term represents the ME effect where an applied voltage generates a charge \(Q\) which changes the anisotropy energy. This phenomenon of voltage-controlled magnetism (VCM), can be strain-mediated as in [25] but could also be charge-mediated, orbital-mediated...
Experiment vs circuit model: (a) The results of the self-consistent circuit model for the structure in (b) are in good agreement with the experimental results in [25]. \( V_{\text{ME}} = V_R(H \neq 0) - V_R(H = 0) \). (b) Experimental structure reported in [25] where the piezoelectric (PE) is \( \langle 011 \rangle \)-cut PMN-PT and the ferromagnet (FM) is \( N \) layers of TbCo2/FeCo. The back-voltage is \( V = v_M \mu \) where \( \mu = m_x^2 - m_y^2 \) and the magnetic energy is \( E_m = Q_{PE} v_M \mu \) where \( Q_{PE} \) is the charge on the capacitor \( C_{PE} \). The following parameters are used: Coercivity for FM \( (H_K = 200 \text{ Oe}) \), saturation magnetization \( M_s = 1100 \text{ emu/cc} \), FM thickness, \( t_{FM} = 200 \text{ nm} \), PE thickness \( t_{PE} = 30 \text{ \mu m} \), Area=520 \times 520 \text{ nm}^2, \) Magnetoelastic constant \( B = -7 \text{ MPa} \), PE constant, \( d = 2500 \text{ pC/N} \), permittivity \( \epsilon = 4033 \epsilon_0 \), resistance \( R = 2 \text{ M\Omega} \), back voltage \( v_M = B d t_{FM}/2\epsilon \). In the experiment, magneto-optic Kerr effect (M.O.K.E) is used to show the variation of magnetization, which is compared to the pseudo-magnetization in our simulation. Experimental panel is reproduced with permission of AIP Publishing LLC, from Reference [25].

III. FIELD-FREE OPERATION

In this experiment (Fig. 2b) the magnetic anisotropy energy and the external magnetic field were ingeniously balanced to provide two unique low energy states that represent “0” and “1” and it is evident from Fig. 2a that our equivalent circuit describes the switching process accurately.

Using the same circuit model we would like to suggest the possibility of field-free operation where “0” and “1” are represented by two different easy axes rather than two different magnetization directions. We assume a (100) surface with an anisotropy energy that is modulated by the charge \( Q \) due to an applied voltage:

\[
E_m = (E_A + v_M Q)(m_x^2 - m_y^2)
\]

Regardless of the specific mechanism, a positive induced charge \( Q \) makes \( m_y \) the easy axis so that \( \langle m_x^2 - m_y^2 \rangle = -1 \), while a negative \( Q \) makes \( m_x \) the easy axis so that \( \langle m_x^2 - m_y^2 \rangle = +1 \), and this constitutes the writing operation. The inverse of the same effect gives rise to a back voltage that allows one to read the information. Using (4) we obtain from (1):

\[
V_{\text{IN}} = Q/C_L + Q/C + v_M (m_x^2 - m_y^2)
\]
IN a linear V, this case V_LL the magnetization (radical departure from the standard convention of using V_mV such that C_{magnet} (in Fig. 1a using the circuit model in Fig. 1b with a circular Fig. 3 IN where the input voltage (V\_IN) is swept from -50 mV to +50 mV in 1 \mu s and pseudo-magnetization, \mu is plotted against V\_IN. Separate SPICE simulations for each solid square where an average magnetization is obtained over 100 ns. Exact Boltzmann integral obtained from Eq. 6. (b) Same results for the differential load voltage, \Delta V_L = V_L - V_L(v_M = 0), in this case V_L(v_M = 0) = V\_IN/2. The actual load voltage has a linear V\_IN dependence superimposed on \Delta V_L, similar to Fig. 4. The differential load voltage is shown here for clarity.

Use of this "pseudo-magnetization" \mu = m_x^2 - m_y^2 is a radical departure from the standard convention of using the magnetization (m_x, m_y or m_z) to represent a bit [26], opening up new possibilities for writing and reading.

Indeed, we believe it should also be possible to use other quantities represented by a function f(m_x, m_y, m_z) to represent a bit. Any mechanism giving rise to a term of the form (Q \times f) in the energy expression can be used to write such a bit, and it should be possible to use the inverse effect to read it.

In the next two sections, we show two example uses of the external magnetic field-free operation of the equivalent circuit.

**IV. EXAMPLE #1: TUNABLE RANDOMNESS**

The first example we illustrate using the equivalent circuit of Fig. 1 is obtained by coupling the circuit shown in Fig. 1 with a low-barrier circular nanomagnet that does not have an easy axis (H_K \rightarrow 0) and no energy barrier (E_A = 0) that favors a magnetization axis [27, 28]. The magnetization of such a magnet fluctuates randomly in the plane, in the presence of thermal noise. The read and write mechanisms of the ME effect convert the fluctuations in the pseudo-magnetization \mu to a voltage.

Fig. 3 shows the differential load voltage \Delta V_L vs V\_IN assuming C = C_L = 50 aF and v_M = 10 mV, consistent with the material parameters for the experimental system in Fig. 2b, though the coupling coefficient v_M is chosen somewhat smaller, (such that C_{eff}v_M^2/kT < 1, as we explain in the next section) in order to avoid any hysteresis or memory effects. Alternatively one could use a smaller load capacitance, reducing C_{eff}.

With this choice of parameters, the magnetizations and hence the voltages fluctuate with time, and the averaged values over a time interval of \approx 100 ns match the average results obtained from the Boltzmann probability:

\[ \langle \mu \rangle = \frac{\int_{Q=-\infty}^{Q=+\infty} \int_{\phi=-\pi}^{\phi=+\pi} d\phi dQ \cos(2\phi) \rho(Q, \phi)}{\int_{Q=-\infty}^{Q=+\infty} \int_{\phi=-\pi}^{\phi=+\pi} d\phi dQ \rho(Q, \phi)} \]

where \rho(Q, \phi) = 1/Z \exp[-E(\phi, Q)/kT] and E = Qv_M \mu + (1/2C_{eff}) - QV\_IN represents the total energy. We assume that the magnetization for the circular in-plane magnet is confined to the plane of the magnet due to the strong demagnetization field. Therefore, the magnetization integral can be taken in the plane (\phi \rightarrow \pm \pi) and this seems to be in good agreement with the numerical s-LLG results as shown in Fig. 3. The average load voltage is obtained using Eq. 6, but replacing cos(2\phi) with Q/C_L.

Eq. 6 does not seem to reduce to a compact closed form, but assuming Q = C_{eff}(V\_IN \pm v_M \mu) \approx C_{eff}V\_IN for small v_M, allows a direct evaluation:

\[ \langle \mu \rangle \approx \frac{I_1(x)}{I_0(x)} \]

where I_n is the modified Bessel function of the first kind [29], and x = Qv_M/kT. This approximation (not shown) seems to be in good agreement with an exact numerical evaluation of Eq. 6 that is shown in Fig. 3 and could be useful as an analytical guide.

Note that the SPICE simulation solves the magnetization and the load voltage self-consistently following the equivalent circuit (Fig. 1a) while the Boltzmann law takes these self-consistencies into account exactly. The agreement between the two constitutes another important benchmark for our equivalent circuit.

With additional gain and isolation that can be incorporated by CMOS components this field-free voltage-
tunable randomness can become a potential voltage controllable “p-bit” (probabilistic bit) that can be used as a building block for a new type of probabilistic logic [30–35] or other neuromorphic approaches that make use of stochastic units [36–41], but this is not discussed further.

V. EXAMPLE #2: NON-VOLATILE OPERATION

It is easy to see by integrating Eq. 6 that even when one uses a stable magnet ($E_A > 40 \, kT$) in Eq. 4, the pseudo-magnetization ($\mu$) does not show “hysteretic” behavior as function of $V_{IN}$, but simply shifts the sigmoid response of Fig. 3 to the left or right depending on the sign of $E_A$. The average sigmoidal behavior of Fig. 3 is not just a consequence of using circular magnets, even a 40 $kT$ magnet would show non-hysteretic behavior, but with suppressed fluctuations in $\mu$ and a shift along the $V_{IN}$ axis. To obtain hysteretic behavior for the pseudo-magnetization $\mu$ we need an energy term that is quadratic ($\sim \mu^2$) rather than linear ($= E_A \mu$) as in Eq. 4, but we will not discuss the possibility further in this paper. Next we show that the energy expression we have used could lead to hysteretic behavior if the ME coefficient $v_M$ were large enough. Such a quadratic term could arise naturally from the physics which we hope motivates future investigation.

Fig. 4 shows the results of a transient simulation of the equivalent circuit with a circular magnet, similar to Fig. 3 with the only difference that in this example the back-voltage ($v_M$) is increased to 100 mV such that $C_{eff}v_M^2/kT \gg 1$. An input voltage is slowly swept from $-200$ mV to $+200$ mV and back to $-200$ mV within 1 $\mu$s, where pseudo-magnetization ($\mu$) and the load voltage ($V_L$) show hysteresis, similar to the magnetization of an ordinary magnet. One way to understand the hysteretic behavior is to note that the total energy for the full circuit in Fig. 1 can be written as:

$$E_{total} = \frac{Q^2}{2C_{eff}} + Qv_M \mu - QV_{IN}$$

where $C_{eff}^{-1} = C^{-1} + C_L^{-1}$.

Expanding Eq. 7 for small $v_M$, we can approximate the pseudo-magnetization by $\mu \approx -Qv_M/(2kT)$ and we have:

$$E_{total} \approx \frac{Q^2}{2C_{eff}} - \frac{Q^2v_M^2}{2kT} - QV_{IN}$$

suggesting that the ME effect provides a negative capacitance $-kT/v_M^2$ in series with $C_{eff}$ leading to hysteretic behavior when $C_{eff}v_M^2 > kT$ reminiscent of similar behavior based on ferroelectrics [42, 43].

Numerical simulations of the equilibrium fluctuations of this magnet also show that the thermal stability of the $\mu$ is $\approx C_{eff}v_M^2/kT$ which can be 60 or greater, for reasonable values of $v_M$ and $C_{eff}$ providing the possibility of non-volatile memory applications based on the pseudo-magnetization $\mu$.

VI. CONCLUSION

In summary, we have presented an equivalent circuit for magnetoelectric read and write and showed that it describes recent experiments on the MELRAM device quite accurately. We then used this circuit model to illustrate the possibility of representing “1” with different easy axes, encoded by the pseudo-magnetization $\mu$, rather than with different magnetizations, allowing a natural field-free operation that can be useful for a number of applications in stochastic neuromorphic computing. Lastly, we showed the possibility of using the pseudo-magnetization for non-volatile memory applications.
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6

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