Transient Negative Inductance in Ferromagnetic Material

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In recent years, negative capacitance has risen in popularity with its effect manifesting in ferroelectric materials and its promise of paving a way to create more energy efficient electronics. This prompts the question of existence of a dual, which is negative inductance (NI). As seen in simulations and convincingly in experiment, this manifests as a momentous drop in current with increase in flux, or momentous rise in current with decrease in flux, for which this phenomenon can be appropriately named as "transient negative inductance". This work effectively captures the behaviour of a ferromagnetic (FM) inductor in transient when it changes in polarization.

The Landau based single domain model and the Ising based multi-domain model both showcase the qualitative behaviour of a negative inductor. In Landau based model, ferromagnets are bistable single domain system with a double well energy landscape, with two stable states representing spin up and spin down states of FM [Figure #]. The energy-flux relation is described by equation [1]. For the time-dependent switching on magnetic field, Landau-Ginzburg equation [2] is used.

$$U = \alpha\phi^2 + \beta\phi^4 - \phi I_L \qquad -(1)$$

$$\rho\frac{d\phi}{dt} = -\frac{dU}{d\phi} \qquad -(2)$$

To see the transient NI effect clearly, square current waveform is used to excite the inductor. A low resistance is added to slow down the transient period. The results obtained are shown in Figure #. The S curve corresponds to the transient NI switching hysteresis.

Ising model is a multi-domain model for ferromagnetic materials which consider each dipole in the FM to be an individual entity. A 3D Ising model is used to simulate the toroid used in the work. Figure # shows the results obtained from the Ising model simulation and the corresponding lattice switching at different instances. Transient negative inductance is observed in the simulation results of the qualitative model in the multidomain FM.

The FM inductor used in the work has a square loop hysteresis pattern (Figure #), since square loop can effectively capture the transient states, rather than flat hysteresis loops. The core is excited with a current driven by a Source Meter Unit (SMU). The circuit diagram of the experimental set up is shown in Figure #. The results match with the qualitative results from the Ising model.

References:

[1] (Example) S. Hirata, Y. Sakai, K. Masui, H. Tanaka, S. Y. Lee, H. Nomura, N. Nakamura, M. Yasumatsu, H. Nakanotani, Q. Zhang, K. Shizu, H. Miyazaki, C. Adachi, Nat. Mater. **14**, 330 (2015).
[2] tutorial paper
[3] asif khans paper
[4] some paper on ising model?!

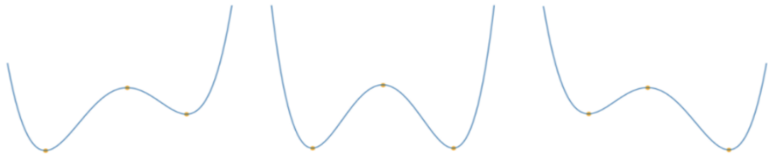

Figure 1: Double well energy landscape of single domain ferromagnet, the change illustrates the polarization switching on applied external magnetic field

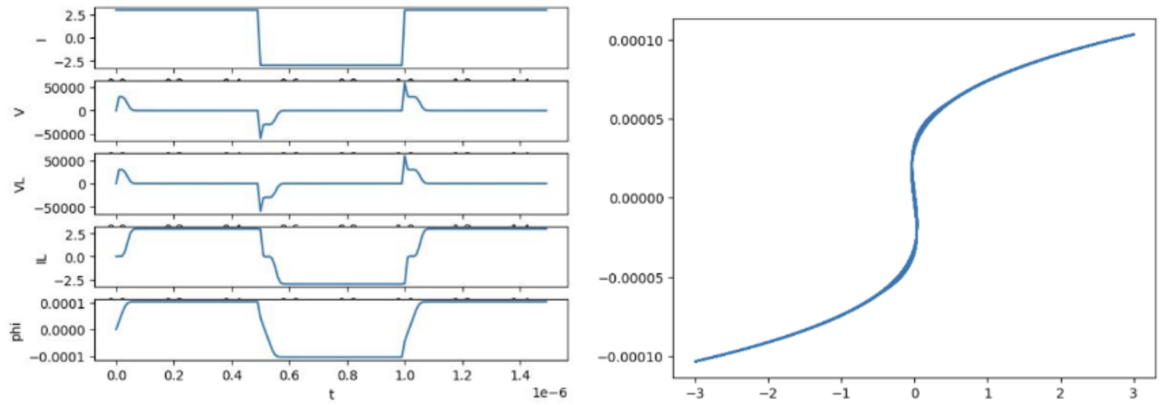

Figure 2: landau model, S-curve

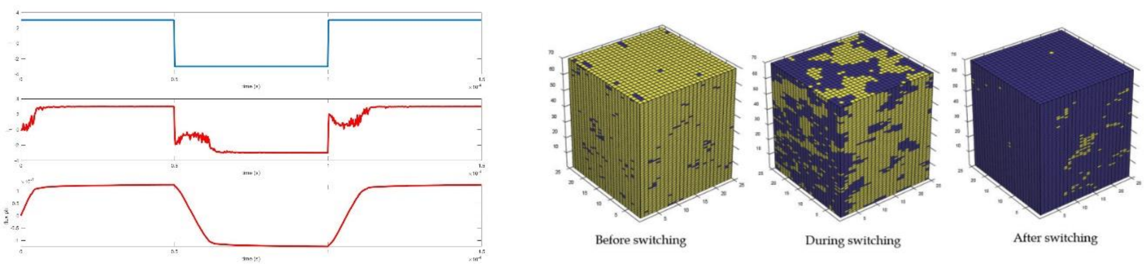

Figure 3: Ising model simulation results, the region highlighted represents the region where negative inductance is observed, the corresponding change in switching of spin is illustrated

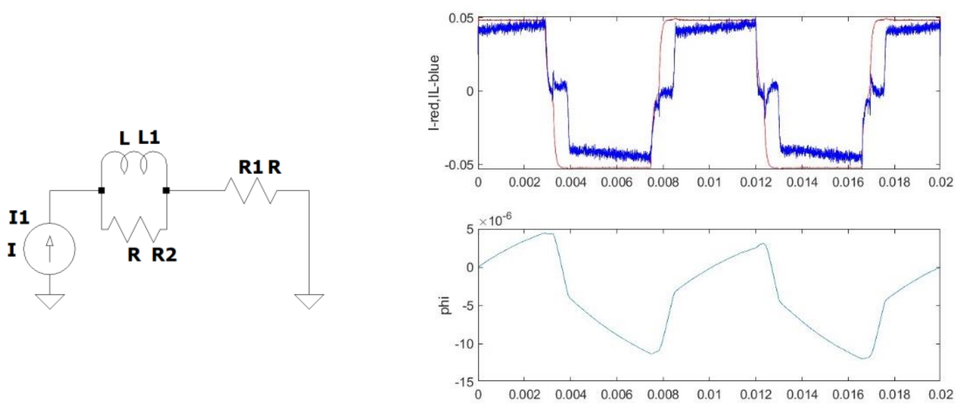

Figure 4: The experimental results showing the transient negative inductance behavior