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Negative Capacitance in Ferroelectric Materials and Implications for Steep Transistors

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Abstract

If a solid state negative differential capacitance can be realized, then it could act as a transformer, 'stepping' up the voltage at the internal node of two series capacitors. In this paper, we shall argue that the stored energy in a ferroelectric material could lead to a solid state negative capacitance. Many applications are possible with such a device. Here we shall emphasize potential use for steep transistors and discuss our recent experiments on the fundamental nature of negative capacitance in ferroelectric materials

1. Introduction

Ferroelectric materials are characterized by an energy barrier between two minima-often known as the W-shaped energy landscape as shown in Fig. 1(a). This energy landscape makes sure that the ferroelectric material could remain polarized even without an applied electric field. It is also due to the W-shaped energy landscape that a ferroelectric material could show negative differential capacitance while in non-equilibrium. The state of negative capacitance is unstable, but just as a series resistance can stabilize the negative differential resistance of an Esaki diode, it is also possible to stabilize a ferroelectric in the negative differential capacitance state by placing a series dielectric capacitor. In this configuration, the ferroelectric acts as a 'transformer' that boosts up the input voltage. The resulting amplification could lower the voltage needed to operate a transistor below the limit otherwise imposed by the Boltzmann distribution of electrons [1-5].

2. Brief discussion of the concept of negative capacitance:

We start by noting that capacitance is, by definition, a small signal concept -- capacitance C at a given charge Q_F is related to the potential energy, U, by the relation $C=[d^2U/dQ_F^2]^{-1}$. Due to this reason we shall henceforth use the term 'negative capacitance' rather than 'negative differential capacitance'. For a ferroelectric material, as shown in fig. 1(a), the capacitance is negative only in the barrier region around $Q_F=0$. Starting from an initial state P, as a voltage is applied across the ferroelectric capacitor, the energy landscape is tilted and the polarization will move to the nearest local minimum. Fig. 1(b) shows this transition for a voltage which is smaller than the coercive voltage, V_c. If the voltage is larger than V_c, one of the minima disappears and Q_F moves to the remaining minimum of the energy landscape (Fig. 1(c)). Notably as the polarization rolls downhill in Fig. 1(c), it passes through the region where $C=[d^2U/dQ_F^2]^{-1}<0$. Therefore, while switching from one stable polarization to other, a ferroelectric material crosses through a region where the differential capacitance is negative.

In this talk we shall discuss about how the negative capacitance state can be probed by (i) stabilizing the state by a series capacitor and then doing steady state measurements of capacitance and (ii) by doing a time dependent measurement and seeing the ferroelectric passing through the negative capacitance region in time. For both cases we shall discuss our recent experimental results. We shall also discuss possible implementations with MOSFETs and the challenges as we see it.

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References

[1] S. Salahuddin and S. Datta, Nanoletters, 8,2,2008.
[2] S. Salahuddin and S. Datta, IEDM, 2008.
[3] Rusu et. al., IEDM, 2010.
[4] AI Khan et. al, APL, 99, 113501, 2011.
[5] AI Khan et al, IEDM 2011.

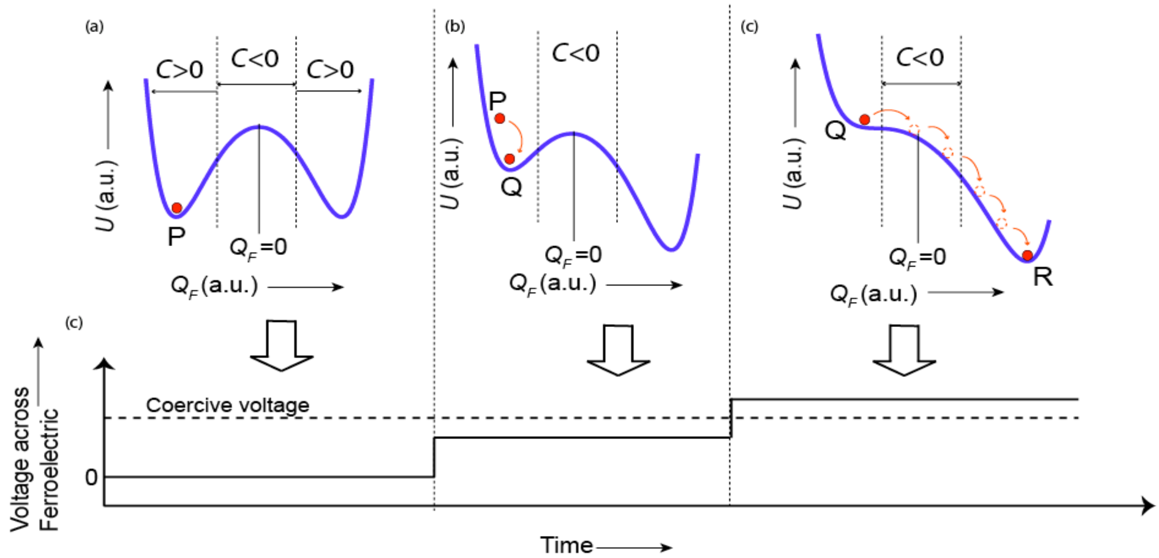

Fig 1: (a) The W-shaped energy landscape of a ferroelectric material that forms due to phase transition. The capacitance is negative only in the barrier region around $Q_F=0$. (b,c) The energy landscape tilts when a voltage is applied. Two cases are shown when the applied voltage is (b)smaller and (c) larger than the coercive voltage. For the latter case, the ferroelectric polarization rolls down hill through the negative capacitance states.