Ferroelectrics, Negative Capacitance and Depolarization Field: What exactly is negative capacitance?

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2019 marks the 11th year since the concept of ferroelectric negative capacitance was first proposed [1]. It was proposed as a physics solution to an engineering problem: The power dissipation in electronics and computing. Yet, it was unique in that the technology required a fundamental scientific discovery in a field that was ~90 years old at that time—the discovery of negative capacitance or static negative permittivity in ferroelectrics. Initially, interests into negative capacitance were limited to the device researchers; over time, the topic brought together the "often-disjoint" communities of device engineers, condensed matter physicists and material scientists in exploring, understanding and finally discovering this phenomenon [2-7]. Different manifestations of the negative capacitance phenomenon, namely, capacitance enhancement, negative differential relation between charge and voltage as well as atomic scale mapping of the stabilized, negative capacitance states corroborated with phase field and density functional theory based calculations have established this concept on a solid ground.

It is indeed an exciting time for researching negative capacitance given its technological importance in the era where scaling "as we used to know it" is ending. Major semiconductor companies are actively investigating/pursuing negative capacitance transistors, and vibrant activities are underway in the academic device research community. At the same time, it is fair to say that the device community is equally divided on fundamental aspects of negative capacitance. "What exactly is negative capacitance?" "Is this a "real" physical phenomenon or an artifact of measurements?" are indeed topics of intense, thought-provoking discussions in most of the recent device conferences. These are all fair questions since ferroelectrics—even in the widely studied, archetypal ones in their cleanest and highest quality, epitaxial forms—are indeed complicated materials; in fact, complexities therein span multiples of orders of length scale. Nonetheless, it is intuitive to visualize a ferroelectric as a set of electric dipoles whose direction of alignment can be switched by an applied electric field. However, how this intuitive picture connects to the negative capacitance or the static negative permittivity behavior of these dipoles can be non-intuitive, and may often seem like a leap of faith. For the phenomena of negative capacitance to truly innovate semiconductor devices and computing, these fundamental physics questions need to be addressed and understood to their full depths. Towards that end, developing an intuitive and simple—yet true to its physics—description of ferroelectric negative capacitance is the crucial starting point.

In first part of the talk, we will attempt at providing an intuitive and physical picture of the origin of negative capacitance/static negative permittivity in ferroelectrics—that rather simple, electrostatic interactions between the microscopically polarizable units (such as unit cells) sets up a positive feedback mechanism which, in turn, leads to this phenomenon. In fact, we will show that the very reason why a ferroelectric develops degenerate, spontaneous polarization states below its Curie temperature is the underlying negative capacitance mechanism—i.e., a ferroelectric exists because it exhibits "unstable" negative capacitance/static negative permittivity.

In the second part of the talk, we will attempt at demystifying the role of the depolarization field in stabilizing negative capacitance in a ferroelectric-dielectric heterostructure. It is well-understood that depolarizing field is responsible for breaking ferroelectric layers into oppositely polarized domains posing a retention challenge in ferroelectric memories [8]. We will show that, in a ferroelectric-dielectric heterostructure, it is a carefully tuned depolarization field arising due to the dielectric layer that stabilizes the ferroelectric negative capacitance and provides the passive voltage amplification. In experimental ferroelectric-dielectric heterostructures, the system can indeed break into domains as understood conventionally. However, such a multi-domain state can still preserve its negative capacitance state due to the domains not being polarized at the spontaneous polarization values (as in isolated ferroelectic layers). We will provide an intuitive picture as to how the balance between the domain wall energy and the depth of the ferroelectric potential well will lead to a multi-domain ferroelectric-dielectric heterostructure that exhibits negative capacitance.

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