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Tailoring of the coercive voltage in a ferroelectric polymer capacitor

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ABSTRACT

For an identical ferroelectric material, operation at a different voltage means that all ferroelectric films should be designed for different thicknesses, though this increases the degree of process complexity. Here, a technique which can be used to adjust the coercive voltage (V_C) of a metal-ferroelectric film-metal capacitor is demonstrated. The V_C-adjustable capacitor was fabricated with ferroelectric polymer film and the capacitor consists of two sub-capacitors with different thicknesses. For a common top and bottom electrode, the sub-capacitors are equivalent to two parallel-connected capacitors. With regard to the variance of the ratio of the area of the sub-capacitors, a V_C-adjustable capacitor can take coercive voltage between two V_C values, each of which correspond to the V_C value of each respective sub-capacitor. In this demonstration, the width of the tuning range of the V_C values was 3.6 V. In addition, the strategy for a linear V_C adjustment of a V_C-adjustable capacitor is discussed in terms of the concept of nonlinearity. This demonstration with a ferroelectric polymer is predicted to be applicable to emerging organic electronic applications.

1. Introduction

Ferroelectric materials are very attractive materials for a range of applications, such as memory devices [1,2] as well as nonvolatile circuits [3], neuron-mimicking circuits [4,5], tunable antennas [6], sensors and actuators [7,8]. If these components can be combined in a single system, such an integrated system will be very versatile. If only one type of ferroelectric material is used, the ferroelectric films for different devices should be fabricated with different thicknesses because different devices operate in different voltage ranges. In other words, all ferroelectric devices should be fabricated with different process steps. Given this point of view, a method by which all ferroelectric devices can be fabricated in a single step but where all devices can operate in different voltage ranges should be encouraged, leading to a reduction in the overall number of process steps and an improvement of the process yield.

In this work, a method to tailor the coercive voltage using a ferroelectric polymer is demonstrated. The coercive voltage is one of the main parameters in ferroelectric films; it is defined as external voltage which creates net polarization of a ferroelectric film zero. The polarity of the surface charge in a ferroelectric film changes upon coercive voltage, which is why coercive voltage is used as a reference (or its corresponding voltage is) to compare ON and OFF states in switching devices or 0 and 1 states in memory devices. The ferroelectric polymer used here was selected for its superior properties, such as easy processability and environment inertness. Therefore, it is expected that tailoring the coercive voltage in a ferroelectric polymer capacitor will be a useful method for emerging applications. In the next section, the principle used to tailor the coercive voltage will be described in detail.

2. Principle

For a ferroelectric capacitor with large surface roughness, it has been reported that the switching time of polarization is retarded compared to a ferroelectric capacitor with a flat surface, as an external electric field is applied non-uniformly to the ferroelectric film [9]. The method to tailor the coercive voltage of a ferroelectric capacitor was inspired by the non-uniform distribution of the electric field. Fig. 1 describes the principle behind the tailoring of the coercive voltage of a ferroelectric capacitor. Fig. 1a represents a normal ferroelectric capacitor with a flat surface, where the two terminals are connected to an external voltage (V_A) source and the ground, respectively. In reality, however, surface roughness exists to a certain extent on account of the crystallinity of the ferroelectric film. For a conceptual understanding, assume that the film morphology consists of only two terrains, a plateau and a valley. The height of the plateau from an electrode connected to the ground is Δ_B above a reference thickness of t_0. Conversely, the valley is positioned below Δ_A from t_0. If all plateaus and valleys correspond to parallel-connected capacitors, the ferroelectric capacitor in Fig. 1b is electrically equivalent to the ferroelectric capacitor shown in Fig. 1c. Therefore, the entire ferroelectric capacitor with an area of A_0 consists of two different sub-capacitors, C_A and C_B. When external voltage V_A sweeps from 0 to V_{MAX}, as represented in Fig. 1d, the coercive voltage of C_A (V_{CA}) is applied prior to the coercive voltages of C_B (V_{CB}). Assume that

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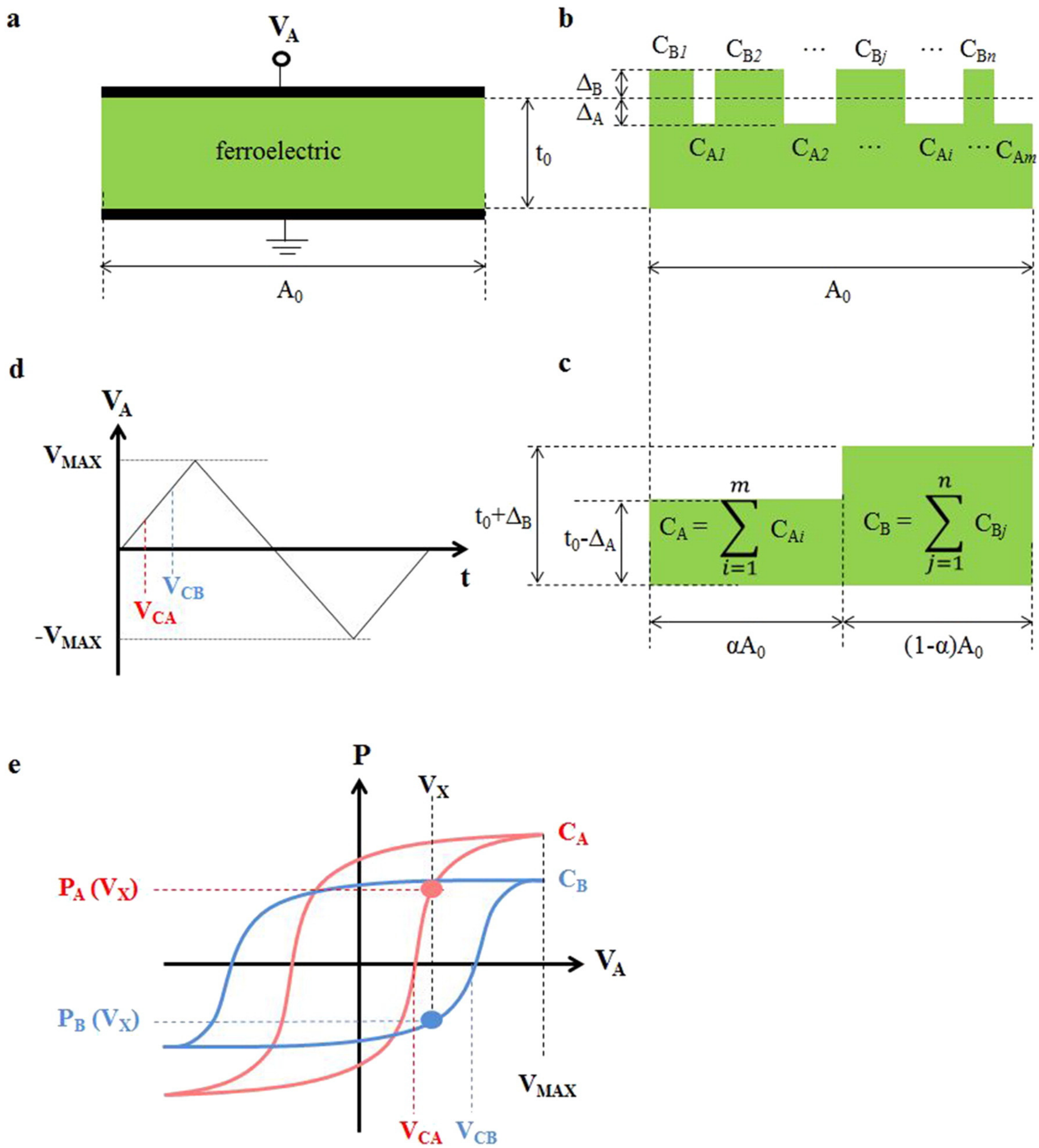

Fig. 1. Principle behind the tailoring of the coercive voltage. Schematics of (a) a flat ferroelectric capacitor with area A_0 and thickness t_0. (b) A rough ferroelectric capacitor with two terrains, a plateau and a valley. The film thicknesses of the plateau and the valley are $t_0 + \Delta_B$ and $t_0 - \Delta_A$, respectively. (c) Structure electrically equivalent to the structure depicted in (b). The area ratio of C_A and C_B is α: 1- α. (d) Profile of the applied voltage with the maximum voltage V_{MAX}. V_{CA} and V_{CB} indicate the coercive voltages of C_A and C_B, respectively. (e) Schematic of the polarization-voltage relationship between C_A and C_B when α exceeds 0.5.

the area ratio of C_A to C_B is α: (1- α). For an α value larger than 0.5, each hysteresis loop for C_A and C_B will be measured, as shown in Fig. 1e. It is possible to imagine that a certain voltage V_X between V_{CA} and V_{CB} exists to make the polarization of C_A at V_X ($P_A(V_X)$) equal to the polarization of C_B at V_X ($P_B(V_X)$). Therefore, it is certain that the coercive voltage of the entire ferroelectric capacitor with area A_0 is positioned between V_{CA} and V_{CB}. Ferroelectric polarization (P) can be quantitatively described with a hyperbolic tangent function, as expressed below [10,11].

$$P = P_S \tanh(k(V_A - V_C)) \quad (1)$$

Here, P_S is the spontaneous polarization of the ferroelectric capacitor when the external voltage V_A is V_{MAX}; V_C is the coercive voltage. The fitting constant k determines how fast P approaches Ps. Thus, P_A and P_B are modelled as $\alpha P_S \tanh(k(V_A - V_{CA}))$ and $(1-\alpha)P_S \tanh(k(V_A - V_{CB}))$, respectively. To apply $V_A = V_X$ to make the net polarization zero throughout a ferroelectric capacitor, the following equation applies.

$$P = P_A + P_B = \alpha P_S \tanh(k(V_X - V_{CA})) + (1-\alpha)P_S \tanh(k(V_X - V_{CB})) = 0 \quad (2)$$

When the parameter k and the capacitor structure are known, the only variable in Eq. (2) is the area ratio, α. In other words, the solution of Eq. (2) depends solely on α to determine the areas of the two capacitors.

The fact that the term α can be manipulated intentionally suggests that it is possible to fabricate a ferroelectric capacitor with random values of the coercive voltage $V_C = V_X$ between V_{CA} and V_{CB}. If such an important factor V_C can be manipulated simply by tuning the area