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Dependence of an electric capacitance on the constant voltage $C = f(U)$ in pure bentonite, composites and semiconductors

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Abstract

The present paper is devoted to studying the effect of dc voltage on the amount of electrical capacitance in pure bentonite, composites and semiconductors with different conductivity, as well as the dependence of electrical conductivity on the external field. The reason for the dependence of the capacitance on the DC voltage may be the presence of potential barriers in them and the dependence of the electrical conductivity (σ) on the applied voltage. In those samples where there is a large range of variation of σ, there are also large changes in electrical capacitance. The principle of a change in electrical conductivity, a change in the electrical capacitance is observed, can be successfully used in microelectronics, electrical engineering, etc. Created capacities parameters can changed in a wide range of voltage and temperature.

1 Introduction

The effect of "negative capacitance" is observed in different semiconductors: in diodes with a Schottky barrier NiSi2 ~ *n*-Si [1], NiSi2—*n*-Si, Pd-*n*-Si, Pd-*n*-GaAs [2], WNx-*n*-GaAs [3], and Al-*n*-GaAs [4]. In the structure of the metal–dielectric–metal type, "negative capacitance" is observed at relatively high electric fields. The mechanism of the "negative capacity" of various composites is different and, in general, not well understood. However, in [4, 5], it is noted that the emergence of a "negative capacitance" is associated with a change in current when a step of constant or alternating voltage is applied. Studies of the dependence $C = f(U)$ are also not proposed in the literature in the proposed scale. The dependence of electric capacity on a constant voltage $C = f(U)$ is noted in [6–8]. Capacity growth with an increase in the constant voltage is associated with an increase in the number of domains moments, which are oriented in the direction of the electric field. At large values of the electric field, the domains "heal" (as the authors put it) for this reason, the capacitance decreases with increasing field strength. Islet metal films have a high low-frequency effective dielectric constant ($\varepsilon = 107 \div 108$) [7], and it is a positive value. The conductivity of island metal films increases under the influence of an external electric field (anomalous conductivity effect) [5]. Since the dielectric constant of conducting systems is largely determined by their conductivity, the dielectric constant of island films must change with the change of the electric field. At the same time, with an increase in conductivity (with an increase in the electric field), the positive part of the effective dielectric constant of metallic films should decrease, and the negative part should increase in absolute value.

2 Materials and methods

To identify the mechanisms of the influence of constant voltage on the electrical capacity of materials, pure polymer films (polyethylene, propylene, polyvinylidene fluoride), composites based on polyethylene and silicon, composites based on bentonite and magnetic microparticles (refined siderite) and montmorillonite clay (bentonite), semiconductors with various thickness and conductivity, *n*-Ge, *n*-İnAs, *n*-Si, *p*-Si were investigated. The bentonite of the Dash-Salakhlinskoye field (Azerbaijan) was modified in a certain amount at turnover, 6000 rpm for 30 min, and the ferrite particles were modified in two modes: 6000 rpm (M1) and 3000 rpm (M2) for 10 min in a planetary mill type FRITSCH. Then, by mixing the powders of the components, discs of a size were compressed: length 16 mm, diameter 7 mm. Composites consist of 50% M1 + 50% (unmodified bentonite, NB) and 50% M1 + 50% (modified bentonite,

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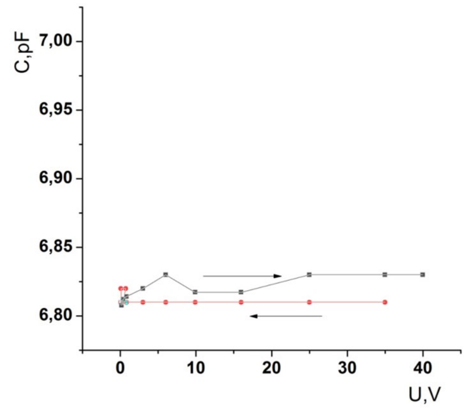

Fig. 1 Dependence of electric capacity on the applied constant voltage for a pure PE film

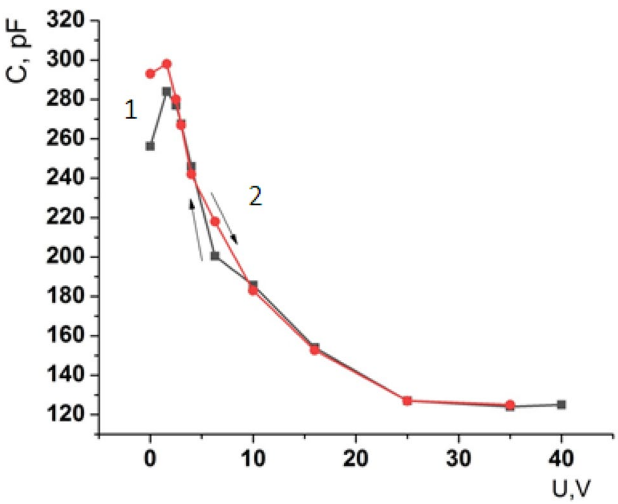

Fig. 2 Dependence of electric capacitance on applied constant voltage for the *n*-Ge sample

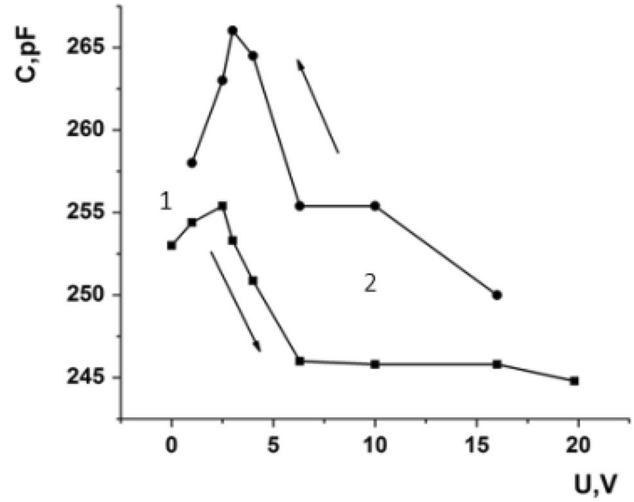

Fig. 3 Dependence of electric capacity on the applied constant voltage for pure bentonite

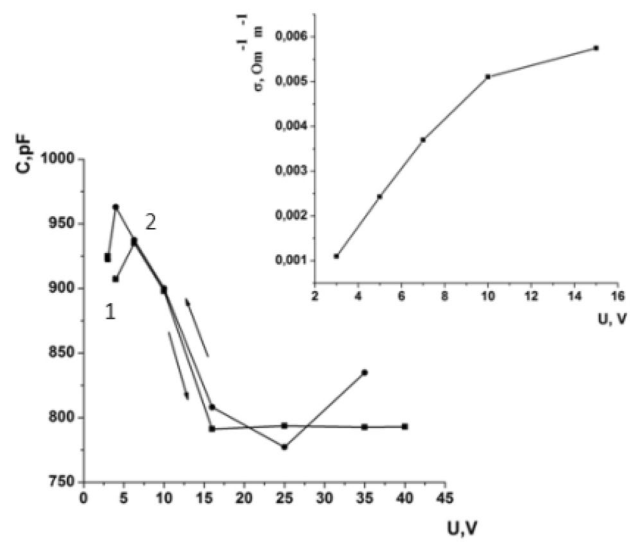

Fig. 4 Dependence of electric capacity on the applied constant voltage for *p*-Si

MB). The thickness of the composites was equal to 180 mm. Samples were in the form of discs (washers) with a thickness of 1.5 mm and a diameter of 7 mm. The disks were pressed without heating at room temperature under a pressure of 1 GPa. To study the electrophysical characteristics, measuring electrodes made of silver paste were applied to both ends of the pressed discs.

The dependences of capacitance and electrical conductivity on constant voltage for all samples at room temperature ($T = 293$ K) were investigated.

From the analysis of the experimental results, the effect of a constant voltage on the parameters under study, the dependence of the electrical capacitance and electrical conductivity on the magnitude of the constant voltage (Figs. 1, 2, 3, 4, 5) was revealed. In dielectric films of polyethylene, polyvinyldenfluoride, the capacitance is almost independent of the magnitude of the constant voltage. For composites based on bentonite and magnetic particles, pure bentonite and pn-type semiconductors, the electrical capacitance increases, reaches a maximum, and then further increases, and the dc voltage decreases (Figs. 2, 3, 4, 5, 6, 7).

3 Results and discussion

In [9, 10], the concept of the presence of potential wells during metal–semiconductor contact [8, 11], semiconductor–semiconductor, filler-matrix (composites), etc., was

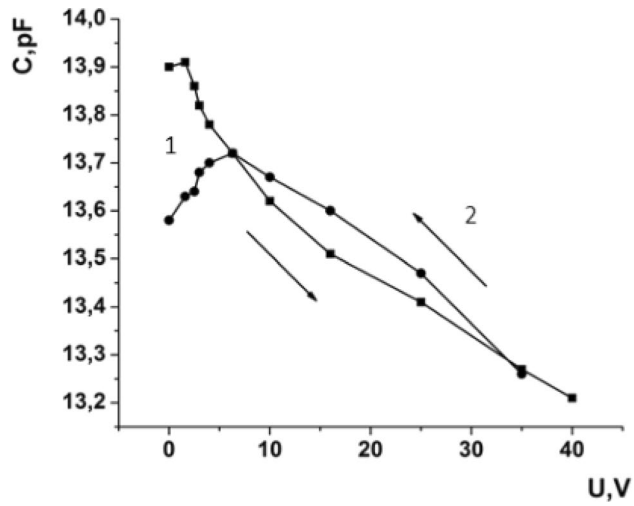

Fig. 5 Dependence of electric capacity on the applied constant voltage for the composite based on 60% of unmodified bentonite and 40% of magnetic particles (6000 rpm) (M1)

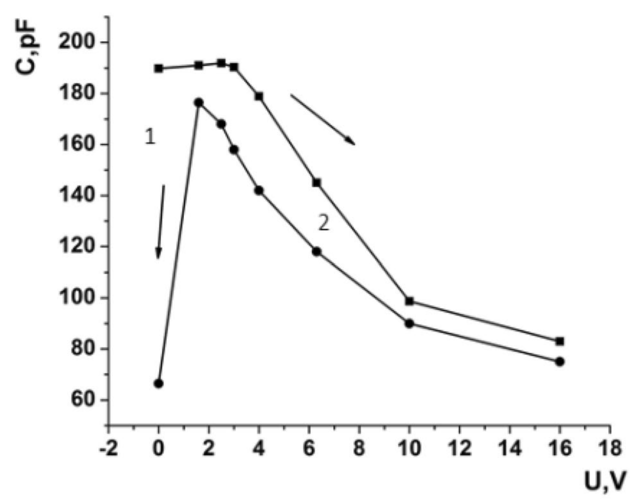

Fig. 7 Dependence of electric capacity on the applied constant voltage for the composite based on 60% of unmodified bentonite and 40% of magnetic particles (3000 revolutions) (M2)

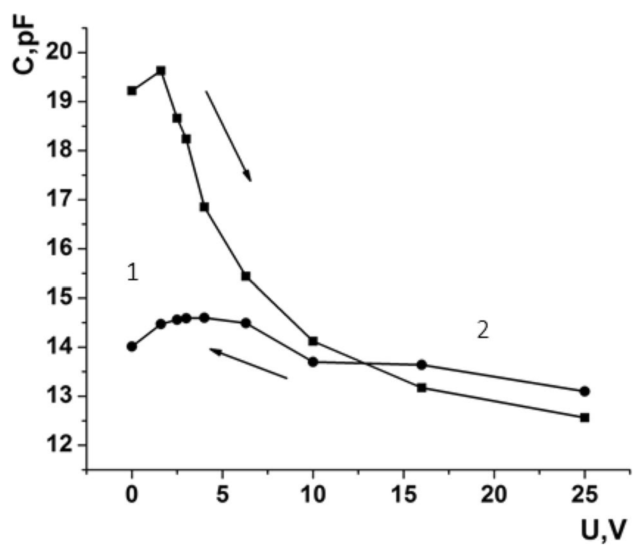

Fig. 6 Dependence of electric capacity on the applied constant voltage for the composite based on 60% of modified bentonite and 40% of magnetic particles (6000 rpm) (M1)

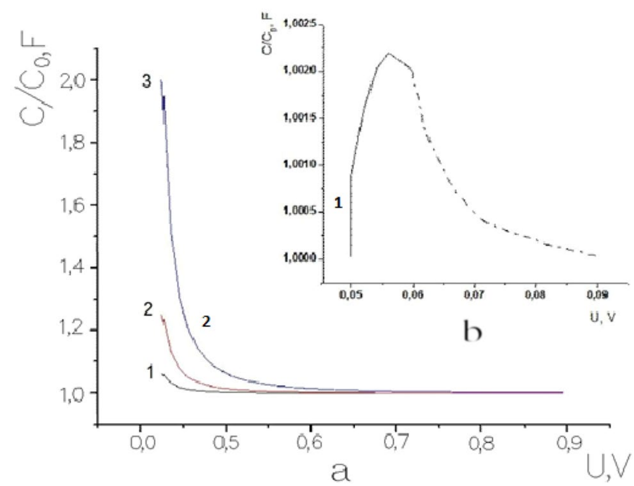

Fig. 8 Theoretical calculation of the dependence of electric capacity on a constant voltage: **a** $U>4U_0$ [$U_0=0.05$ (1); $U_0=0.1$ (2); $U_0=0.2$ (3)], **b** $U\leq 4\ U_0$ ($U_0=0.05$)

introduced. In [9], the capacitance–voltage characteristic in nonlinear resistors (varistors) based on ZnO is explained by the presence of potential barriers (pits) in them and a theoretical formula is derived for the dependence of the capacitance on the U/U_0 ratio:

$$\left(\frac{C}{C_0}\right)^2=\frac{1}{2}\left\{1+\frac{1}{16}\left(\frac{U}{U_0}\right)^2+\sqrt{\left[1+\frac{1}{16}\left(\frac{U}{U_0}\right)^2\right]^2-\frac{1}{4}\left(\frac{U}{U_0}\right)^2}\right\} \tag{1}$$

where C_0 is the original capacitance (F), U_0 is the height of the potential barrier (B), and U is the external field (B).

It can be seen from formula (2) that the C/C_0 ratio depends on the U/U_0 ratio, namely, at $U\leq 4U_0$, capacity begins to increase, and at $U>4U_0$, capacity decreases. Using formula (1), we carried out a theoretical calculation of the dependence of the capacitance on the magnitude of the external field. In this case, the ratio U/U_0 at $U\leq 4U_0$ and $U>4U_0$ is considered.

For the theoretical calculation of C/C_0, the C++ program was used. The calculation results are shown in Fig. 8a, b. From Fig. 8b, it can be seen that at $U\leq 4U_0$, the electric capacitance rises and reaches a maximum ($U_0=0.05$). When

Table 1 Change of an electric capacitance and electrical conductivity of the samples (in percent)

Name of sample	Changing of C и σ	
	C, pF (%)	σ, $Ом^{-1}см^{-1}$ (%)
Pure dielectric film	0.14	0.17
Pure bentonite	5.5	6
Composite based on 60% unmodified bentonite and 40% magnetic particles (6000 rpm) M1	4.5	6
Composite based on 60% modified bentonite and 40% magnetic particles (6000 rpm) M1	33	38
Composite based on 60% unmodified bentonite and 40% magnetic particles (3000 rpm) M2	50	55
p-Si	17	20
n-Ge	60	65

$U > 4U_0$, the capacitance decreases with increasing applied voltage. In this case, calculations are given for different values of U_0 ($U_0 = 0.05$; 0.1; 0.2) (Fig. 8a). According to [10], the dependence of the electrical conductivity on the external field in such structures is well described by the Poole–Frenkel formula:

$$\sigma = \sigma_0 \exp \frac{e^{3/2}\left(U/_d\right)^{1/2}}{\sqrt{4\pi\varepsilon\varepsilon_0}} \tag{2}$$

where σ_0 is the conductivity in a weak electric field, U is a constant voltage (V), d is the sample thickness (m), ε is the dielectric constant, ε_0 is the dielectric constant, $\varepsilon_0 = 8.85 \times 10^{-2}$ F/m. As can be seen from formula (2), with an increase in the electric field, the electrical conductivity σ grows exponentially.

The presence of potential wells in them (U/U_0 ratio), as well as the dependence of electrical conductivity on a constant voltage, plays an important role in changing the electrical capacitance of media.

As seen in Fig. 1, with an increase in the constant voltage, the capacitance value of the dielectric film does not change much (see Table 1). The observed increase in capacity is in good agreement with theoretical calculations (Fig. 8b, area 1). In this region, the condition $U \leq 4U_0$ is satisfied (in the calculation, $U_0 = 0.05$ is assumed).

A decrease in the capacitance in the same samples with an increase in the constant voltage also qualitatively agrees with the theoretical calculations of the capacitance using formula (1) (Fig. 8a, region 2). In other words, the condition $U \geq 4U_0$ is satisfied in this area.

It should be emphasized that a change in the electric field can strongly influence the magnitude and sign of the electric capacitance. With an increase in the electric field, the height of the potential barrier decreases, as a result of which the number of charge carriers increases and thereby increases the value of electrical conductivity ($\sigma \sim n$) [9, 10]. Since the electric capacitance is directly proportional to the dielectric constant ($C \sim \varepsilon$), the electric field indirectly affects the magnitude and sign of the electric capacitance. In those samples (structures) where there is a large range of variation of σ, there are also large changes in electrical capacitance (see Table 1). Regardless of the nature and production in the samples studied, the dependence of the electric capacitance on the magnitude of the constant voltage was found. The reason for the dependence of the capacitance on the DC voltage may be the presence of potential barriers in them and the dependence of the electrical conductivity (σ) on the applied voltage.

4 Conclusions

The data obtained allow us to conclude that the electric capacitance is indirectly dependent on the electrical conductivity, with a large change in electrical conductivity, a change in the electrical capacitance is observed. This principle can be successfully used in microelectronics, electrical engineering, etc. Capacities can be created, resistance parameters, which can be changed in a wide range of voltage and temperature.

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