*Journal of Engineering Physics and Thermophysics, Vol. 76, No. 1, 2003*

# CHARGE PROPERTIES OF A CONDENSER SYSTEM BASED ON THE TWO-LAYER DIELECTRIC $SiO_2$–$Ta_2O_5$

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UDC 539.2116.2

*A variant of a combined dielectric for the condensers of very large-scale integrated circuits (VLSICs) has been proposed. Its electrophysical and mechanical properties have been analyzed. The influence of the thickness of each of the dielectrics on the effective built-in charge, the permittivity, and the threshold voltage has been considered. Special emphasis has been placed on the residual mechanical stresses in a three-layer dielectric system, namely, the influence of the thickness of a* $Ta_2O_5$ *film on the radius of curvature of the* $Si$–$SiO_2$–$Ta_2O_5$ *system has been analyzed and the dependence of the change in the effective built-in charge in the* $Ta_2O_5$ *film on the radius of curvature of the plate has been determined.*

Dielectrics are the main element of the condensers of integrated circuits, which determine their parameters and properties. The material of a dielectric must possess a high electric strength, a small dielectric loss, a high permittivity, and a necessary frequency response; it must satisfy the requirements of a technological process. Condenser dielectrics can conditionally be divided into two groups:

1) traditional dielectrics widely used at present — silicon oxide $SiO_2$, silicon nitride $Si_3N_4$, and silicon oxynitride — the technology of deposition of which is well developed [1];

2) nontraditional dielectrics, among which one can single out the oxides of transition elements and rare-earth elements, composite and ceramic dielectrics, and dielectrics based on ferroelectric materials [2].

The modern trend in microelectronics toward a decrease in the size of the elements of integrated circuits has generated the need for a more detailed investigation into the problem on the use, as condenser dielectrics, of materials with a higher permittivity than that of traditional $SiO_2$ and $Si_3N_4$. The oxides of transition metals are superior to silicon oxide, silicon nitride, and silicon oxynitride in many parameters; because of this, much attention is being given to the investigation into the possibility of using them in planar technology. Of greatest interest is tantalum pentoxide $Ta_2O_5$ [3] and its combinations with the traditional dielectric $SiO_2$ [4].

To study the properties of the combined dielectric $SiO_2$–$Ta_2O_5$, we prepared samples with various combinations of the thicknesses of silicon-oxide and tantalum-pentoxide films. At first, we formed the $SiO_2$ films by different methods of oxidation: dry, wet, and pyrogenic oxidation. We produced films 30, 50, and 100 nm thick by the method of oxidation in dry oxygen and films 40, 50, 100, and 200-nm thick by the method of oxidation in wet oxygen; films 50, 100, and 220 nm thick were produced by pyrogenic oxidation. To increase the number of variants of $SiO_2$–$Ta_2O_5$ combinations we divided plates with grown silicon-oxide films into sectors to form a pentoxide-tantalum film of a certain thickness in each separate sector. Thus, several combinations of $SiO_2$–$Ta_2O_5$ films were formed on one plate. Then, tantalum films having different thicknesses (30 to 90 nm) were deposited on the silicon-oxide films by the method of electron-beam sputtering; for producing tantalum pentoxide, these films were subjected to oxidation in a dry-oxygen atmosphere at a temperature of $900^{o}C$. The thickness of the $Ta_2O_5$ films produced after the oxidization of Ta was 75 to 250 nm.

To study the influence of the thickness of each dielectric in a combined dielectric film on the electrophysical parameters of the ternary $Si$–$SiO_2$–$Ta_2O_5$ system, we investigated the following electrophysical parameters of the samples obtained: effective built-in charge $Q$, permittivity $\varepsilon$, and threshold voltage. Analysis of the change in the value and sign of the charge in the combined dielectric structures shows that $Q$ remains positive in all the combinations. In

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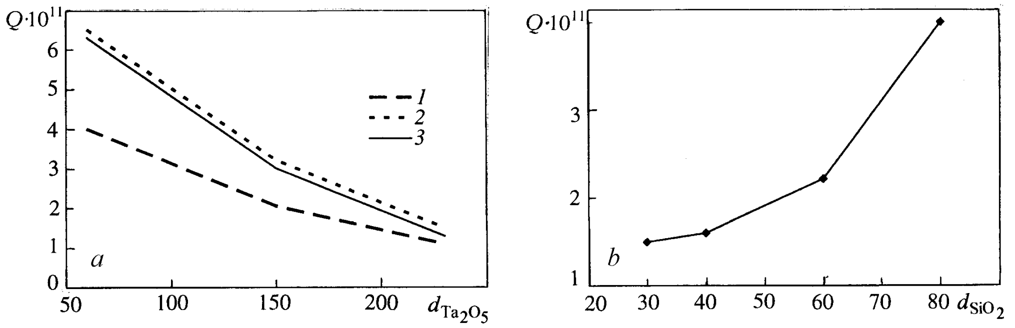

Fig. 1. Dependence of the change in the effective built-in charge in the $SiO_2$–$Ta_2O_5$ system on the thickness of the $Ta_2O_5$ films [1) the $SiO_2$ film has been produced in dry oxygen, 2) in wet oxygen, and 3) by the method of pyrogenic oxidation] (a) and on the thickness of the $SiO_2$ film (b).

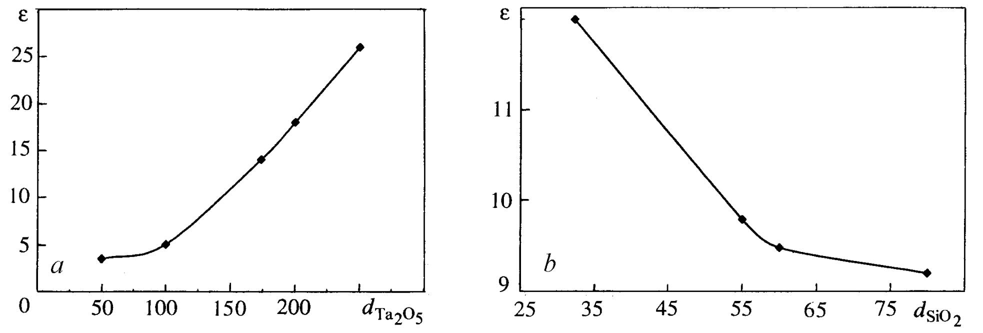

Fig. 2. Dependence of the change in the permittivity in the $SiO_2$–$Ta_2O_5$ system on the thickness of the $Ta_2O_5$ film (a) and $SiO_2$ film (b).

this case, it reaches a maximum value of $6.5 \cdot 10^{11}$ $cm^{-2}$ on the plate with the silicon oxide grown in wet oxygen, and a minimum value of $1.1 \cdot 10^{11}$ $cm^{-2}$ is observed on the plate with the silicon oxide grown in dry oxygen. The thickness of the tantalum-pentoxide film is maximum here and is equal to 213.7 nm. Study of the dependence of the change in the charge in the combined dielectric on the thickness of tantalum pentoxide shows that $Q$ tends to decrease at all the combinations of the thicknesses of the $SiO_2$ ($d_{SiO_2}$) and $Ta_2O_5$ ($d_{Ta_2O_5}$) films in the group of plates on which silicon oxide has been grown by the method of dry oxidation (Fig. 1a). The maximum positive charge is $4.0 \cdot 10^{11}$ $cm^{-2}$ in the combination where $d_{SiO_2}$ is larger than $d_{Ta_2O_5}$ (79.4 and 69.6 nm). The minimum positive charge, $1.1 \cdot 10^{11}$ $cm^{-2}$, was observed in the combination where the thickness of the $SiO_2$ film was much smaller than the thickness of the $Ta_2O_5$ film (34.6 and 217.2 nm). In the group of plates on which silicon oxide has been grown by the method of wet oxidation, the value of the positive charge also decreases from $6.5 \cdot 10^{11}$ $cm^{-2}$ for $d_{Ta_2O_5}$ equal to 66 nm to $1.5 \cdot 10^{11}$ $cm^{-2}$ for a maximum thickness of tantalum pentoxide of 208.0 nm. In the group of plates on which silicon oxide has been grown by the method of pyrogenic oxidation, $Q$ decreases from $6.3 \cdot 10^{11}$ $cm^{-2}$ to $1.5 \cdot 10^{11}$ $cm^{-2}$. When the thickness of the $Ta_2O_5$ film is constant and the thickness of the $SiO_2$ film varies, the positive charge in the combined film increases. Thus, in the group of plates on which silicon oxide has been grown by the method of dry oxidation, for a constant thickness of tantalum pentoxide (for instance, 70.0 nm) $Q$ increases from $1.5 \cdot 10^{11}$ $cm^{-2}$ for $d_{SiO_2}$ equal to 34.6 nm to $3.5 \cdot 10^{11}$ $cm^{-2}$ for $d_{SiO_2}$ equal to 80.0 nm. In the group of plates where silicon oxide has been grown in wet oxygen for a constant thickness of $Ta_2O_5$ (for instance, 140.0 nm), $Q$ increases from $1.7 \cdot 10^{11}$ $cm^{-2}$ for $d_{SiO_2}$ equal to 39.0 nm to $3.9 \cdot 10^{11}$ $cm^{-2}$ for $d_{Ta_2O_5}$ equal to 186.0 nm (Fig. 1b). The decrease in the positive charge in the combined $SiO_2$–$Ta_2O_5$ film as a result of the increase in the thickness of the tantalum-pentoxide film is due to the compensation for the built-in positive charge of silicon oxide with the negative charge of tantalum pentoxide.

One important characteristic of a dielectric is the permittivity ε. Investigation of the change in ε with the thickness of the tantalum-pentoxide film in the combination $SiO_2$–$Ta_2O_5$ shows that it increases with increase in $d_{Ta_2O_5}$ (Fig. 2a). This increase is tracked in all three groups of plates. The minimum value of ε is 3.8 for the silicon oxide 39.0 nm thick which has been grown in wet oxygen; $d_{Ta_2O_5}$ is equal to 66.0 nm in this case. Here, the permit-

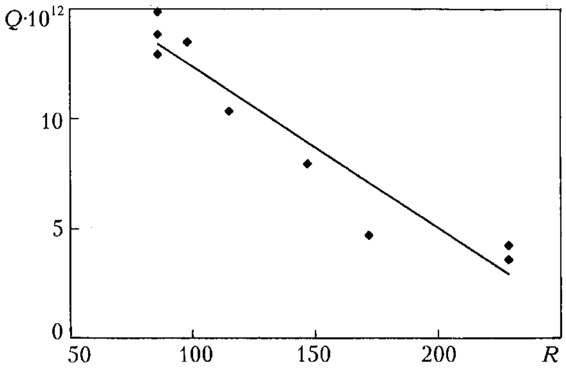

Fig. 3. Dependence of the change in the value of the built-in charge in the $Ta_2O_5$ film on the radius of curvature of the system $R$.

tivity of the combined dielectric approaches ε of the silicon oxide. The maximum value of ε is 26.07 for a $SiO_2$ thickness of 25.0 nm and a $Ta_2O_5$ thickness of 227.7 nm; in this variant, silicon oxide has been grown by the method of pyrogenic oxidation. Considering the combinations of films in which the thickness of the tantalum-pentoxide film remains constant and the thickness of the silicon-oxide film changes, we should note that the value of ε of the combined film decreases with increase in thickness of the $SiO_2$ film. Thus, for $d_{Ta_2O_5}$ equal to 140.0 nm, ε of the combination decreases from 12.0 for $d_{SiO_2}$ equal to 35.0 nm to 9.2 for $d_{SiO_2}$ equal to 80.0 nm (Fig. 2b). The increase in ε of the combined dielectric as a result of the increase in the thickness of the tantalum-pentoxide film is explained by the fact that, in this case, the properties of the combined dielectric begin to approach the properties of the $Ta_2O_5$ film.

Comparison of the values of the threshold voltage and the thicknesses of the tantalum pentoxide films in the dielectric structures studied shows that the threshold voltage increases with increase in $d_{Ta_2O_5}$ from 50 to 250 nm. We should note that the change in the threshold voltage is within 0.2–1.0 V. It is small and points to the fact that the positive charge in the combination of the dielectrics decreases with increase in $d_{Ta_2O_5}$. Had there been no compensation for the positive charge of the $SiO_2$ film with the negative charge of the $Ta_2O_5$ film, the increase in the threshold voltage would have been larger.

Special emphasis was placed on the residual mechanical stresses in the multilayer thin-film system. Of interest was the fact of the influence of mechanical stresses on the charge properties of the combined dielectric. At the first stage, we measured the radii of curvature $R$ of the plates with dielectrics formed. They changed with the thickness of the tantalum-pentoxide film, namely, $R$ decreased when $d_{Ta_2O_5}$ increased, i.e., the curvature of the system increased. Thus, $R$ changed from 172 to 86 m when $d_{Ta_2O_5}$ increased from 70 to 210 nm (in this case, $d_{SiO_2}$ was constant and equal to 350 nm). The three-layer system had a minimum curvature for $d_{SiO_2}$ equal to 188 nm and $d_{Ta_2O_5}$ equal to 660 nm, and the maximum curvature of the system was observed for $d_{SiO_2}$ equal to 350 nm and $d_{Ta_2O_5}$ equal to 210 nm.

We also analyzed the dependence of the change in the charge state in the $Ta_2O_5$ film on the radius of curvature of the system. The analysis has shown that the decrease in the latter leads to an increase in the charge states in the tantalum-pentoxide film. For example, a decrease of 260 to 86 m in $R$ leads to a change of $3\cdot10^{12}$ to $1.3\cdot10^{13}$ $cm^{-2}$ in the value of the charge (Fig. 3).

Thus, the investigations of the electrophysical properties and the mechanical stresses in the three-layer system $Si–SiO_2–Ta_2O_5$ made it possible to establish the following relations:

a) as the thickness of the $Ta_2O_5$ film increases, the effective positive built-in charge in the three-layer system decreases; in this case, the permittivity of the combined dielectric increases and the threshold voltage also increases, even if insignificantly, with increase in the thickness of the $Ta_2O_5$ film;

b) the curvature of the system increases with increase in the thickness of the $Ta_2O_5$ film;

c) the effective built-in charge in the $Ta_2O_5$ film increases with increase in the curvature of the system.

## NOTATION

$Q$, specific effective built-in charge in the dielectric film, $cm^{-2}$; ε, permittivity; $d_{SiO_2}$ and $d_{Ta_2O_5}$, thicknesses of the silicon-oxide and tantalum-pentoxide films, nm; $R$, radius of curvature of the $Si–SiO_2–Ta_2O_5$ system, m.

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