Electrical Properties of Thin $\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$ Films on Silicon Dioxide Substrates

S. V. Razumov, A. V. Tumarkin, M. V. Sysa, and A. G. Gagarin
St. Petersburg State Electrotechnical University, St. Petersburg, Russia
e-mail: thinfilm@eltech.ru
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Abstract—We have studied the electrical properties of thin ferroelectric films of barium strontium titanate ($\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$) obtained on fused quartz ($\text{SiO}_2$) substrates by RF magnetron sputtering. Dependences of the tuning coefficient and dielectric loss tangent on the synthesis temperature and the film thickness are reported. The results are compared to analogous data for films grown on polycrystalline alumina substrates. © 2003 MAIK “Nauka/Interperiodica”.

In recent years, ferroelectrics have attracted much attention as possible materials for microwave devices [1, 2]. This interest is largely due to the strong dependence of the permittivity of ferroelectric materials on the applied electric field strength and the relatively low level of dielectric losses in the microwave frequency range [3, 4]. These properties make such ferroelectrics promising materials for various microwave devices, such as varactors, phase-shifting devices, tunable filters, and phased antenna gratings, capable of operating at room temperature [5].

Thus, ferroelectric films for microwave devices must combine a sufficiently strong field dependence of the permittivity with low energy losses in the microwave frequency range [6]. One of the most promising candidate materials, characterized by highly nonlinear permittivity and a low level of losses, is barium strontium titanate $\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$ (BSTO) [4, 7]. Based on BSTO films, some microwave devices such as phase shifters [8, 9] have been successfully implemented, and some others (filters, delay lines, etc.) are now being extensively developed.

An important factor in designing microwave devices is the selection of a proper dielectric substrate for BSTO films. Widely used substrate materials for microwave devices are single crystal (sapphire) and polycrystalline (polycor) alumina [6, 7]. We believe that good prospects are also offered by quartz substrates, which are characterized by low dielectric losses and stability of permittivity. The low permittivity of quartz (as compared to that of sapphire and polycor) allows the dimensions of microwave elements to be varied within broad limits, thus facilitating the optimum system design in the range of frequencies above 30 GHz. However, the problem of depositing ferroelectric films onto quartz substrates is still not solved.

This letter reports on a comparative study of the electrical properties of BSTO films obtained by the method of ion-plasma sputtering on polycrystalline alumina (polycor) and fused quartz (silica) substrates.

The samples of BSTO films were prepared by RF magnetron sputtering of $\text{Ba}_{0.3}\text{Sr}_{0.7}\text{TiO}_3$ ceramic targets with a diameter of 76 mm. The target composition was selected based on the results of our previous investigations [7], where the range of technological parameters ensuring the synthesis of ferroelectric films with electrical properties sufficient for microwave applications had been established. The films were deposited in a single technological cycle simultaneously onto quartz and alumina substrates. The substrate temperature during deposition was monitored by a thermocouple fixed on the substrate holder. The holder temperature could be controlled in the interval from 700 to 905°C. The deposition time was varied from 100 to 300 min, which corresponded to the film thicknesses (measured with a profilometer) increasing from 3500 to 10500 Å, respectively, at a deposition rate of 35 Å/min. The target–substrate distance was about 40 mm. The process was performed in a pure oxygen atmosphere. After deposition, the samples were cooled in oxygen at atmospheric pressure at a rate of 2–3 K/min. Prior to the working deposition cycle, the targets were pretreated by sputtering for 30 min, during which the substrates were shielded.

The electrical properties of the synthesized films were studied using planar capacitor structures with copper electrodes formed on the film surface by photolithographic techniques. The capacitor structures had the following linear parameters: electrode thickness, 0.5 μm; interelectrode gap width, 6 μm; gap length, 0.8 mm. The sample structures were characterized by the controllability (expressed in terms of the tuning coefficient $n = C(0)/C(E_{\text{max}})$) and dielectric loss level ($\tan \delta$). These electrical characteristics were measured at room temperature and a frequency of 1 GHz. The voltage $U_1$ applied to the capacitors varied from 0 to 300 V, which corresponded to the electric field strength...
in the interelectrode gap being varied within $E = 0$–50 V/mm.

The Curie temperature of the ferroelectric films was ~160°C, which is close to the value for bulk BSTO samples. The zero-field permittivity (calculated as described in [10]) fell within 230–240 for the BSTO films on quartz substrates and ranged within 320–450 for the films deposited onto alumina.

Figures 1a and 1b show plots of the tuning coefficient $n$ and the dielectric loss tangent, respectively, versus deposition temperature $T$ for the films obtained on quartz and alumina substrates. Data for the BSTO films on alumina are presented for the comparison, since high-quality BSTO films possessing good electrical properties on this substrate material have been obtained previously [7]. As can be seen from Fig. 1, the levels of controlability and losses tend to increase with temperature for films on both quartz and alumina substrates. It is interesting to note that a similar trend was observed for the BSTO films on sapphire substrates [6, 7]. This analogy suggests that the BSTO films grown on the materials reported here and on the substrates used previously [7] obey common laws. In the case of deposition onto quartz substrates, the tuning coefficient reaches maximum ($n = 1.95$) for the films grown at 905°C. Further increase in the temperature of synthesis is expedient only from the standpoint of increasing controllability, since the energy losses ($\tan \delta = 0.025$ at 1 GHz) in the films deposited at 905°C onto quartz substrates already exceed the level acceptable for microwave applications [6].

Figures 2a and 2b present the plots of the tuning coefficient $n$ and the dielectric loss tangent, respectively, versus thickness for the BSTO films deposited at a temperature of $T = 905°C$ on the quartz and alumina substrates. As seen from these data, both the controllability and the microwave energy losses tend to increase with the film thickness. The level of losses is higher for the films grown on quartz than for those on alumina. The increased level of losses in the samples deposited onto quartz is probably explained by the insufficiently high quality of the BSTO films grown on these amorphous substrates and by a significant difference in the coefficients of thermal expansion of the ferroelectric film and quartz substrate. Indeed, the thermal expansion coefficient of polycor ($75 \times 10^{-7} \text{K}^{-1}$) is close to that of a BSTO film ($94 \times 10^{-7} \text{K}^{-1}$), so that the film is subject to insignificant straining as a result of the substrate heating and cooling and, hence, no additional structural defects are formed in the film material. In contrast, the thermal expansion coefficient of quartz ($5.5 \times 10^{-7} \text{K}^{-1}$) is more than one order of magnitude lower as compared to that of the BSTO film [11]. As a result, the BSTO film grown on a quartz substrate exhibits cracking on cooling. The cracks are readily observed in an optical microscope and revealed by film thickness measurements in a profilometer. These additional defects lead to an increase in the level of losses.

![Fig. 1. Plots of (a) the tuning coefficient $n$ and (b) the dielectric loss tangent versus BSTO film synthesis temperature $T$ for the samples grown on (1) alumina (polycor) and (2) quartz substrates.](image1)

![Fig. 2. Plots of (a) the tuning coefficient $n$ and (b) the dielectric loss tangent versus BSTO film thickness for the samples grown at a temperature of $T = 905°C$ on (1) alumina (polycor) and (2) quartz substrates.](image2)