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High-Frequency Characteristics of $SrTiO_3$ Thin Films in the mm-Wave Band

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High-frequency dielectric characteristics of $SrTiO_3$ (STO) thin films deposited by an ECR sputter on semiconductor substrates are studied. Dielectric constants measured for the STO thin films is from 20 to 125. These are kept constant at a frequency range up to 50 GHz. The *Qf* value is constant in the mm-wave band and is estimated to be comparable to that of bulk materials. STO thin films are found for the first time to be applicable to MMICs operating in the mm-wave band.

1. Introduction

Dielectric thin films with large dielectric constants on semiconductor substrates have been extensively studied for applications such as high-frequency bypass on-chip capacitors[1] or DRAM memory cells.[2] The dc-leakage of the thin films is usually investigated as this determines the quality of the thin films. The operating frequency of the devices ranges from MHz to hundreds of GHz. The high-frequency characteristics of the thin films reported, however, have only been restricted in a frequency range of several GHz.[1] The dielectric characteristics in higher frequency ranges are only known for bulk materials using the dielectric resonator method.[3] The possibility of dielectric dispersion at around several GHz was reported[4] for some kinds of dielectric thin films. The evaluation of high-frequency characteristics of dielectric thin films is an important topic to allow application to devices. High-frequency dielectric characteristics of STO thin films in the mm-wave band are presented in this paper.

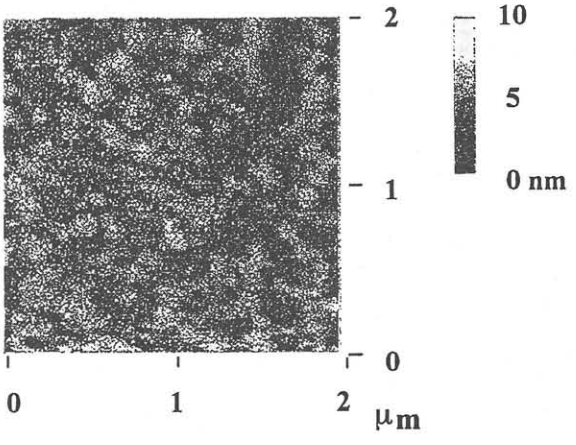

Fig. 1. AFM image of STO thin film surface. Deposition temperature is 300 °C.

2. Experiments

The STO thin films were deposited on semi-insulating InP substrates at room temperature (RT) or 300 °C in a mixed ambient of argon and oxygen using an ECR sputter. Microwave power and rf power for deposition were both 300 W. Deposition rate was about 1.7 nm/min. The refraction index and surface morphology of STO thin films were examined. The thin film composition was also analyzed.

STO thin film capacitors with several area dimensions and devices designed for correction of the stray around the capacitors[5] were formed simultaneously by conventional MMIC processing. Buffered HF was used to pattern the STO thin films.

Admittances for the thin film capacitors and devices for stray correction were obtained by measuring reflection coefficient (S_{11}), using a network analyzer from 50 MHz to 50 GHz. Subsequently, dielectric constant and dielectric loss were calculated from the measured admittances.

Table 1. Properties of STO thin films.

dep. temp.	surface roughness	refract. index	Sr/Ti
RT	20 nm	1.89	21/19 %
300 °C	5	2.18	21/19

3. Results

3.1 Thin film properties

Surface morphology of the STO thin film on an electrode deposited at 300 °C, observed by atomic force microscopy (AFM), is shown in Fig. 1. Mean surface roughness for the 300 °C deposition is 5 nm. The higher deposition temperature results in less surface roughness. Properties of the STO thin films are listed in Table 1. The higher refraction index results in higher dielectric constant that will be shown later. Composition analysis by Auger electron spectroscopy shows the deposited thin films to be almost stoichiometric.

3.2 High-frequency capacitance and conductance

Typical frequency characteristics of capacitance and conductance are displayed in Fig. 2. Capacitance is kept constant through the whole frequency range measured, while conductance increases as frequency is increased. Constant capacitance reveals that STO thin films do not disperse in frequency ranges up to 50 GHz. Conductance reflects high-frequency dielectric loss due to the phase lag of electric flux density to electric field. Figure 2 gives reasonable results for the STO capacitor. However, additional investigation needs to be performed to obtain consistent results. Measurement or capacitor fabrication can be checked using capacitance dependence on the capacitor area, as shown in Fig. 3. In this figure, capacitance is linear to the capacitance area with a 1±0.01 slope. Irregular device processing or measurement may cause the slope to change from that value in part of or the complete line in Fig. 3.

3.3 High-frequency characteristics of STO thin films

The frequency dependence of dielectric constant ε_r in STO thin films, calculated from capacitance, is shown in Fig. 4. This figure clearly shows that ε_r is constant for an ε_r value range from 25 to 125. STO thin films with several kinds of ε_r values, deposited by the ECR sputter, were proved not to disperse in a frequency range up to at least 50 GHz. The ε_r depends on thin-film thickness as shown in Fig. 5. The value of ε_r for STO deposited at 300 °C decreases rapidly below 100 nm as reported previously,[1] while that for STO deposited at RT is constant. A higher deposition temperature will give a higher ε_r. Deposition temperature below 300 °C satisfies the requirements of the device processing such as those for InP-based MMICs. The values of ε_r obtained here are relatively low, but can give sufficiently low impedance in the mm-wave band. The STO thin films, therefore, can be used for high-frequency bypassing capacitors in the mm-wave band. Although the ε_r for STO deposited at RT is small, its independence on thin-film thickness is important in the practical aspects of device design and processing.

Frequency characteristics of Q and frequency product (*Qf* product) are shown in Fig. 6. Here, Q is approximated to be the inverse of tan δ, which is calculated from the measured values of paired capacitance and conductance. The dielectric loss in STO thin films is apparently larger than that of bulk STOs reported in the literature.[6] The reason for this larger loss may not be due to thin-film loss but to surface loss, considering *Qf* product dependence on thin film thickness at a frequency range above 10 GHz. The dielectric loss of STO thin films deposited by the ECR sputter, therefore, can be estimated to be comparable to that of bulk STO, as the limit of thickness dependence. The *Qf* product value observed above 10 GHz is almost constant, which demonstrates the well-known rule of *Qf* product constancy in regard to frequency. The *Qf* product value below 10 GHz, however, decreases almost linearly and is independent on thin film thickness. The reason for this is not clear at this stage.

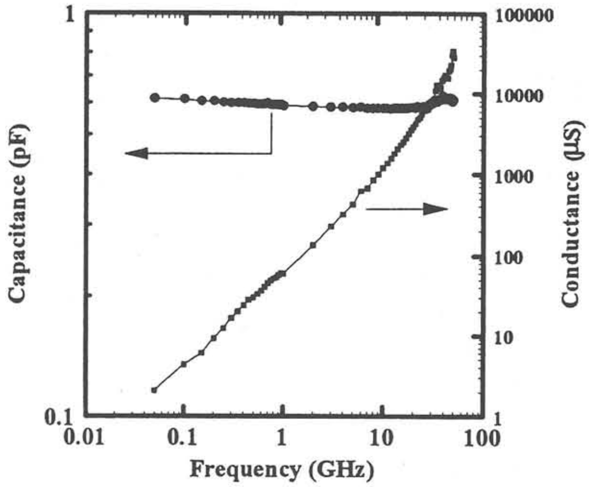

Fig. 2. Typical frequency characteristics of capacitance and conductance for a capacitor with 80 μm^2 area and 65 nm thickness.

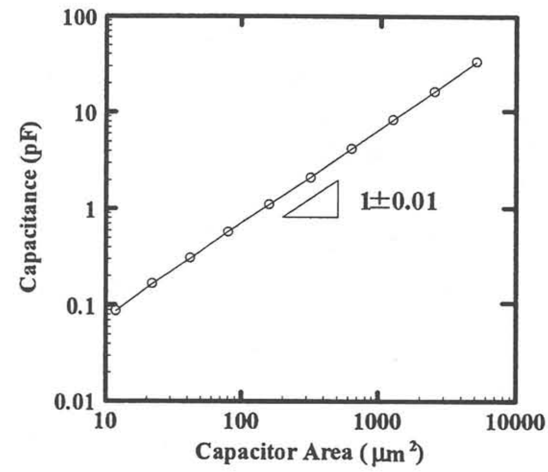

Fig. 3. Capacitance dependence on capacitor area.

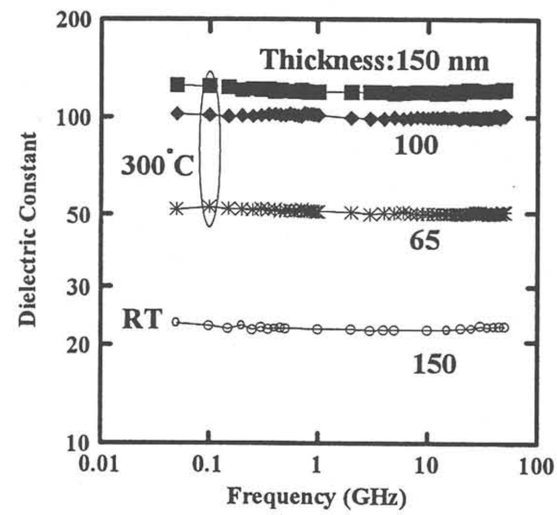

Fig. 4. Frequency characteristics of dielectric constants of STO thin films.

A recent study[7] has pointed out examples which show similar properties to our results. However, further research needs to be conducted to clarify this problem.

4. Conclusion

High-frequency characteristics of STO thin films up to 50 GHz were evaluated for the first time, and STO thin films made by ECR sputter deposition were demonstrated to be applicable to devices which operate in the mm-wave band.

Acknowledgments

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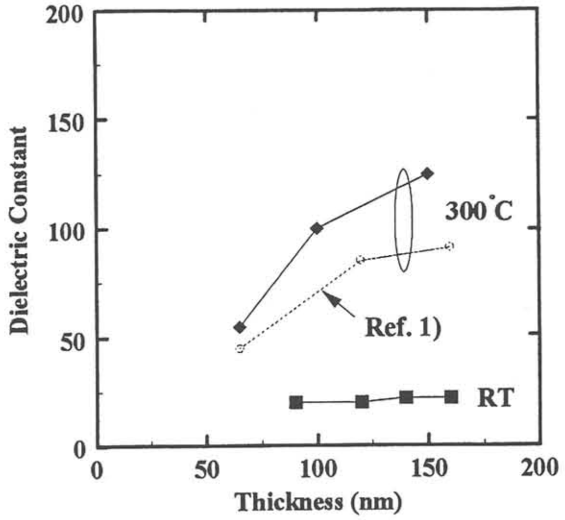

Fig. 5. Dielectric constant dependence on thin-film thickness.

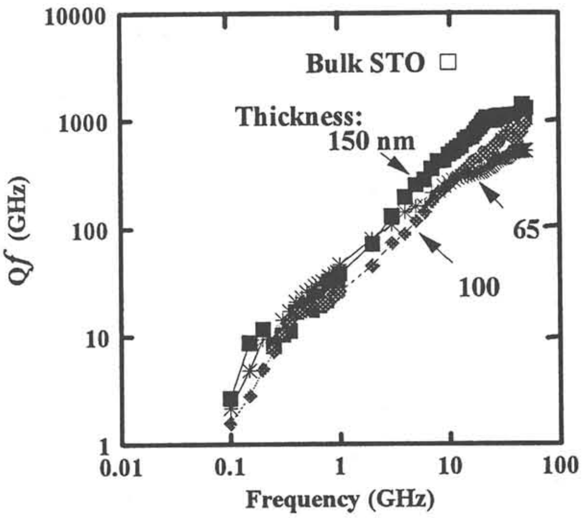

Fig. 6. Frequency dependence of Qf product. Deposition temperature is 300 °C.