

Observation of Long Transients in the Electrical Characterization of Thin Film BST Capacitors

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Charge trapping is responsible for long transient leakage currents observed in parallel plate thin film BST capacitors. The presence of such time dependence complicates the measurement of leakage current as a function of an applied voltage, with the voltage sweep introducing hysteresis in the absence of ferroelectricity. The effect of long transients on current-voltage sweeps is discussed, as well as a method of obtaining current-voltage characteristics in the presence of transient leakage currents.

Keywords: Transient leakage current; barium strontium titanate; BST; hysteresis

INTRODUCTION

Barium strontium titanate (BST) is a solid solution perovskite. In its room temperature paraelectric state, thin film BST has a large field dependent permittivity. Unlike in its bulk form, the permittivity exhibits weak temperature dependence. BST has enjoyed attention over the past few years for memory applications because of its high permittivity, and for use as a tunable dielectric in microwave circuit applications because of its field dependent permittivity.

Because of its perovskite structure, BST has a tendency to form oxygen vacancies. In addition to this source of defects, BST films grown by RF magnetron sputtering in an Ar/O₂ ambient are non-stoichiometric. The argon ions in the plasma are significantly more massive than the sputtered titanium ions, resulting in the scattering of titanium back on to the BST targets. Thus in addition to the expected presence of oxygen vacancies, sputtered films tend to be titanium deficient. The presence of these point defects in BST films results in traps.

Upon the application of a voltage, traps are filled and then release electrons (holes) to the conduction (valence) band over a time scale determined by the trap lifetime and the energy of the trapping level. During leakage current measurements, the emission of carriers from trap levels appears as a transient component in the measured current. We have observed long time scale transient behavior during leakage current measurements, directly by measuring the current at a fixed bias (I-t), and indirectly through its affect on current-voltage (I-V) sweeps.

We have observed the alteration of I-V sweeps by transient leakage currents in three ways: voltage sweep direction dependent characteristics, different characteristics for different voltage step sizes, and different characteristics for variations of the application time for voltage steps. All three of these effects are due to the contributions of a time dependent leakage to a nominally steady state measurement.

EXPERIMENTAL

BST films were grown by RF magnetron sputtering in an Ar/O₂ environment. The Ar and O₂ flow rates were 90 sccm and 10 sccm respectively, and the chamber pressure was adjusted to be between 25 and 50 mTorr. The films were grown on platinized sapphire substrates at 700°C. Two RF guns at 150 W were used, both with either Ba_{0.5}Sr_{0.5}TiO₃ or Ba_{0.3}Sr_{0.7}TiO₃ targets. The growth time for a 100 nm film was 64 minutes.

The processing of the test capacitor structures involved a two-layer mask process. The first layer protects the device areas during a wet etch in 1:1 buffered HF. The second layer defines electrode areas for lift-off. The Pt top contacts to the devices and contacts to the ground plane, deposited by e-beam evaporation, were between 150 and 200 nm thick.

Electrical measurements on capacitors typically consisted of leakage current measurements performed using either a Keithley 6517A electrometer with a series resistance of the order of 100 MΩ or an Agilent 4155B semiconductor parameter analyzer. In addition, capacitance measurements to determine the capacitance density, tunability, and loss tangent were performed using an Agilent 4294A impedance analyzer or a Keithley 590 CV meter.

RESULTS

I-V Measurements

Figure 1 illustrates a common problem with fast leakage current—voltage sweeps. In both plots, the choice of sweep direction plays a role in

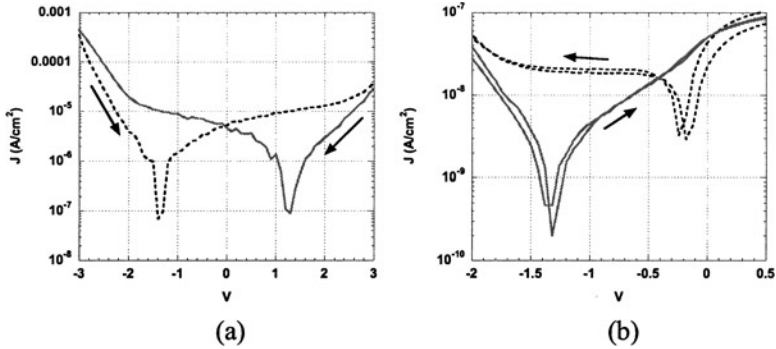


FIGURE 1 Sweep direction dependence in (a) a 100 nm $\text{Ba}_{0.3}\text{Sr}_{0.7}\text{TiO}_3$ film and (b) a 100 nm SrTiO_3 film.

determining the measured characteristic. The current density minima for both sweep directions occur at non-zero applied voltages because of the influence of previous measurement points on each successive measurement point in the respective sweep. Sweeping outward from 0 V would ensure that the minima always occur at 0 V, but it only treats the symptom rather than the underlying problem; in measurements like those depicted in Fig. 1, each data point reflects the device's response to the previous applied voltages in addition to the instantaneous applied voltage. This hysteretic behavior is not due to ferroelectricity; Fig. 1(b) shows the same response in a SrTiO_3 film known to be paraelectric.

The behavior in Fig. 1 can be explained as the result of the applied voltage being swept faster than the time required to obtain a steady state current response. Figures 2 and 3 support this conclusion as well. In Fig. 2, three different characteristics are obtained for sweeps over the same voltage range, which differ only in the application time of each voltage step. In Fig. 3, two different characteristics are obtained for sweeps over the same voltage range with different step sizes, but the same step application time, resulting in different total times required for sweep completion.

The dependence on voltage step application time, as shown in Fig. 2, suggests the existence of a transient response to each applied voltage step. According to the data in Fig. 2, the time scale over which the current is significantly changing must be longer than 1 second, as the 3-second voltage application time results in a lower leakage current. The fact that the leakage current density decreases with increasing voltage step application times means that this time dependent response of the capacitor is not due to resistance degradation; resistance degradation results in an increase in

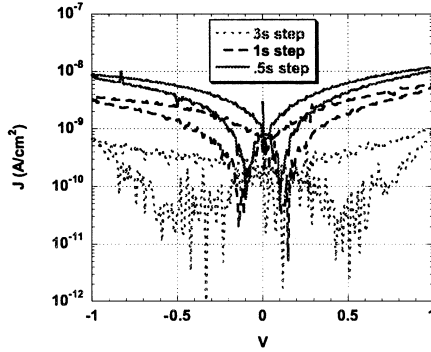


FIGURE 2 Voltage step application time dependence in a 100 nm $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$ film.

leakage with time. Fig. 3 shows data from two different voltage sweeps, which were identical in all parameters except for the voltage step size, with one trace having 0.1 V steps and the other having 0.01 V steps and therefore ten times the number of total steps. Since the steps have the same duration in both traces, the trace with ten times more steps takes ten times longer to complete. The data in Fig. 3 shows that the time required to complete the sweep with the larger step size is shorter than the transient leakage response time of the device.

I-t Measurements

Measurement of current as a function of time shows long time scale behavior. The nature of this behavior varies greatly on the growth and processing

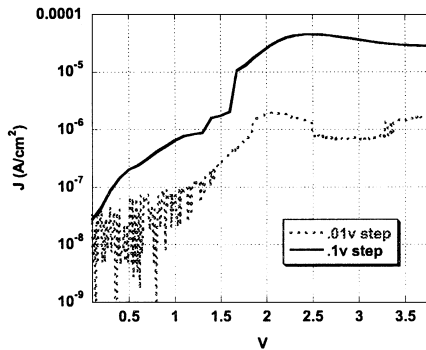


FIGURE 3 Voltage step size dependence in a 100 nm $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$ film.

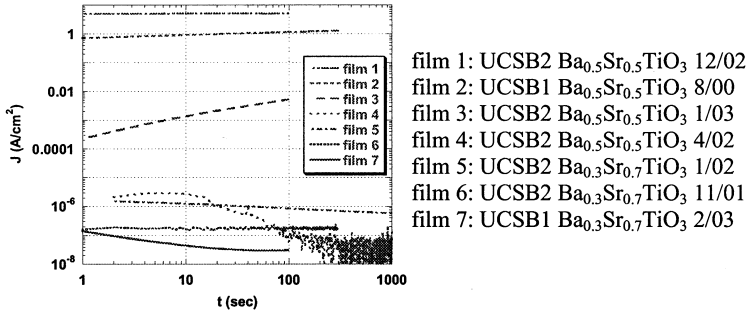


FIGURE 4 Time dependent leakage current density for a variety of films at an applied bias of 200 kV/cm.

conditions of the material. The measurements in Fig. 4 depict this variation. Although the magnitude of the applied electric field is the same for all seven measurements, some of the samples show a monotonically decreasing current, while others show an early onset of resistance degradation. The seven films were all grown in either of the two sputtering systems at UCSB (labeled as UCSB1 and UCSB2) during a two and a half year span. Aside from illustrating the ubiquity of long time scale leakage current transients, Fig. 4 also shows the variation in the properties of films grown at different times; the first five films were sputtered from targets with the same composition yet their leakage current densities span eight orders of magnitude.

Dielectric relaxation can cause long transient currents during measurement, such as those depicted in Fig. 4. A distinguishing feature of such relaxation currents is that the transients measured after the rising edge and falling edges of an applied voltage step should be comparable. The measurement in Fig. 5 shows that the long transients cannot be due solely to dielectric relaxation. After ten seconds, the current measured as a response to the removal of the applied field (J_{depol}) is more than two orders of magnitude smaller than the current measured as a response to the application of the electric field (J_{pol}). Thus not only is the long time behavior attributable to some other cause than dielectric relaxation, the contribution of relaxation currents to the measured transient is negligible after the first few tens of seconds.

The asymmetry in response to rising and falling edges of the voltage pulse in Fig. 5 suggests that some process different from dielectric relaxation occurs in the film during the application of the voltage. An explanation for the asymmetric characteristic is that the applied field sweeps trapped charges out of the film. Emission of trapped electrons (holes) into the conduction (valence) band is consistent with the observed monotonic decrease in measured

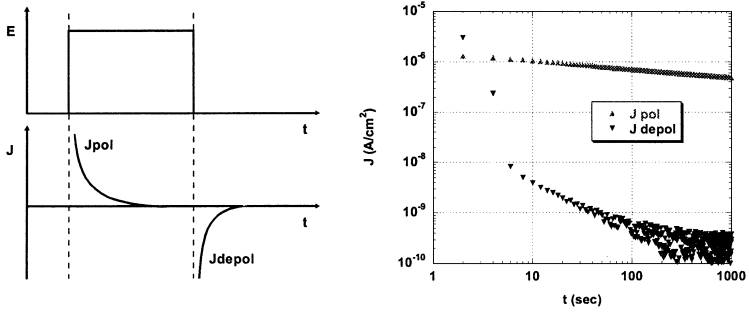


FIGURE 5 Transient leakage response of a 100 nm $\text{Ba}_{0.3}\text{Sr}_{0.7}\text{TiO}_3$ film to the rising and falling edges of an applied 200 kV/cm step.

current as a function of time during the application of a steady bias. The time scale involved in the observation of emission of carriers from traps depends on how deep the traps are, with the contribution of carriers emitted from traps close to the band edges appearing faster than the contribution of deeper trap levels.

Simmons describes the following relationship for isothermal currents [1]:

$$J = \frac{q^{LkT}}{2t} N_n(E_c - kT \ln vt) f_0(E_c - kT \ln vt) + \frac{q^{LkT}}{2t} N_p(E_v + kT \ln vt) [1 - f_0(E_v + kT \ln vt)]$$

Using this expression we see that not only is the time related to the energetic distribution of traps, but that the I-t measurement can give us a direct image of the trap distribution within the band.

The long time scale behavior uncovered by I-t sweeps shows that one needs to be careful when measuring and interpreting I-V measurements. Sweeping the voltage, even with long voltage application times, may be inappropriate in the presence of long transients because it makes subsequent measurement points dependent on previous measurements. The duration of leakage current transients must be evaluated as a component of the I-V characterization process.

I-V Construction

Two different approaches may be taken to acknowledge the effect of transient currents during a voltage sweep. The first method involves holding each voltage step in a sweep for a sufficiently long time that the transient response

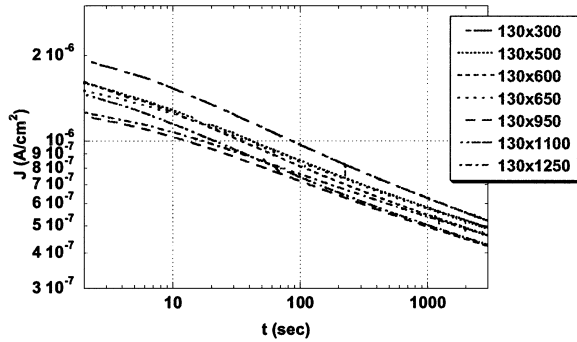


FIGURE 6 J-t measurements for devices with 7 different electrode areas on a 100 nm thick $\text{Ba}_{0.3}\text{Sr}_{0.7}\text{TiO}_3$ film under a steady 2 V bias.

has settled down [2]. In the second method, I-V curves are constructed out of a series of I-t measurements are performed at different biases, with each measurement performed on a new device [3]. When the film properties are known to be relatively uniform and large numbers of devices are available, the second approach is preferable.

An additional benefit of I-V sweep construction from I-t measurements is that when leakage current densities are uniform across a sample, as in Fig. 6, larger devices can be used for smaller bias voltages and smaller devices for larger bias voltages. This allows for the measurement of larger currents at small biases, which results in improved current density resolution. The measurement of smaller biases at larger biases is beneficial as it allows for the experimenter to use the same experimental set up, with low current connections, for measurements over a large range of biases.

Figure 7 shows J-V sweeps at six different points in time, constructed out of J-t measurements. Each bias point represents a J-t measurement on a single device, with all six points in time at each bias from the same measurement. While all six constructed sweeps are qualitatively similar, the onset of breakdown under a positive bias occurs faster at higher voltages and slower at lower voltages, where faster and slower refer to time slice used to construct the I-V sweep. The longer a voltage is applied, the lower the apparent breakdown voltage. This breakdown voltage lowering is coincident with the onset of resistance degradation. In Fig. 8, the positive bias I-t measurements in and around the breakdown region from Fig. 7 are shown. The first I-t measurement exhibiting resistance degradation has a 2 V applied bias, despite the fact that the current initially decreases with time.

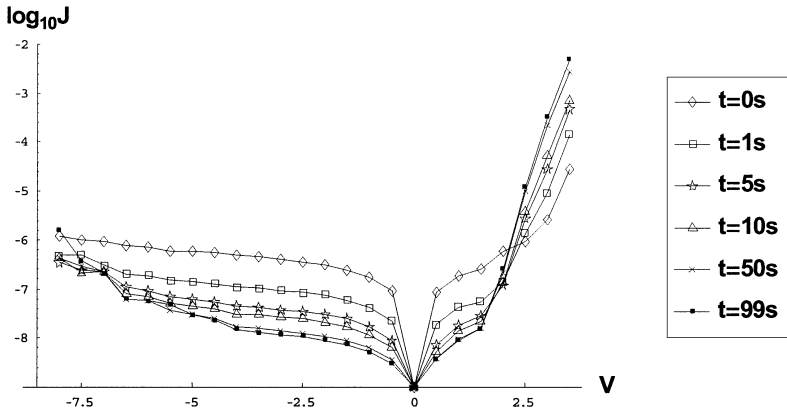


FIGURE 7 Series of J-V sweeps constructed from J-t measurements on a 250 nm thick $\text{Ba}_{0.3}\text{Sr}_{0.7}\text{TiO}_3$ film. (J in A/cm^2).

It is important to recognize that if an I-V sweep is produced by holding each voltage for a long period of time, the cumulative effect of all previously applied voltages will reduce the apparent breakdown voltage. Consider that the measurements in Fig. 8 were each performed on different devices; had a single device been used for all of the J-t measurements we would expect to see resistance degradation at earlier times and/or lower voltages.

CONCLUSIONS

Long time scale transient currents, associated with the emptying of trapping levels, influence I-V measurements. Sweeping outwards from 0 V and

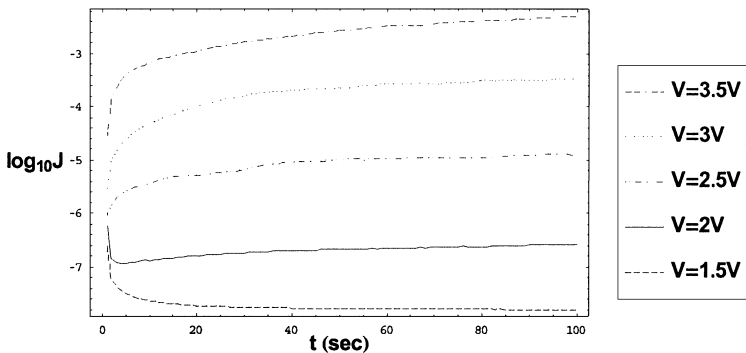


FIGURE 8 J-t measurements on a 250 nm thick $\text{Ba}_{0.3}\text{Sr}_{0.7}\text{TiO}_3$ film. (J in A/cm^2).

holding voltage steps for long times reduce the amount of unwanted hysteresis in I–V measurements, but those techniques fail to address the cause of the hysteresis. I–V sweep construction from independent I-t measurements is a more accurate way to judge the I–V characteristics of a device where long transients cause each measured point in a voltage sweep to be dependent on the accumulated stress of the previous measurement points.

On samples where the film is not uniform or there are few devices, a large number of I-t measurements may not be possible. In those instances our discussion of I-t behavior remains relevant; it behooves the experimenter to consider the effects of resistance degradation upon their measurement as the device approaches breakdown.

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