Optimizing Growth of Lead Zirconate Titanate Thin Films by Pulsed Laser Deposition

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Abstract

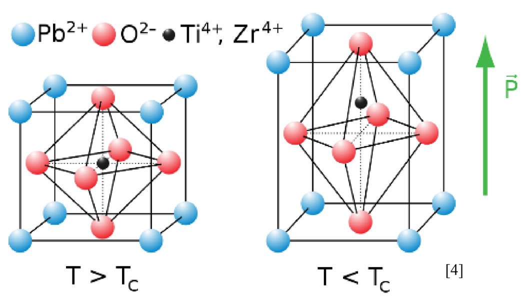
Decreasing power consumption in transistors is of great interest to the electronics industry. A newly suggested architecture incorporating a ferroelectric film into the gate of the transistor has been shown to reduce the subthreshold slope and could lead to more efficient operation. To support these efforts, it is necessary to gain a better understanding of the factors affecting growth of ferroelectric materials. We investigated the effects of changing laser pulse frequency, laser energy, and substrate temperature to determine the optimal conditions for pulsed laser deposition of ultra-thin epitaxial lead zirconate titanate films.

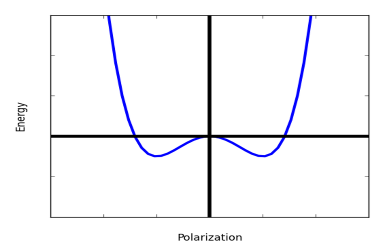
Motivation

Improving the performance of transistors has been a central goal of the electronics industry for many years. One key measurement of performance is the subthreshold swing, S, a measurement of the change in gate voltage required to give a ten-fold increase in source-to-drain current. Previously, it was believed that 60mV/decade represented an absolute minimum for S at room temperature. Consequently, a much larger voltage had to be applied to the gate of a transistor than is theoretically required to transmit signals throughout the chip [1]. Since power is proportional to the square of voltage, this "voltage mismatch" represents a huge inefficiency. However, Salahuddin and Datta presented a novel approach to eliminating this mismatch, demonstrating that, in theory, a thin layer of a ferroelectric material could be used to amplify the voltage experienced in the channel of the transistor [2]. Recently, Jo et al. demonstrated this effect experimentally, measuring values of 18mV/decade for a transistor incorporating an organic ferroelectric layer in the gate [3]. Lead zirconate titanate is another promising ferroelectric for this application, but films of sufficient purity are not yet available.

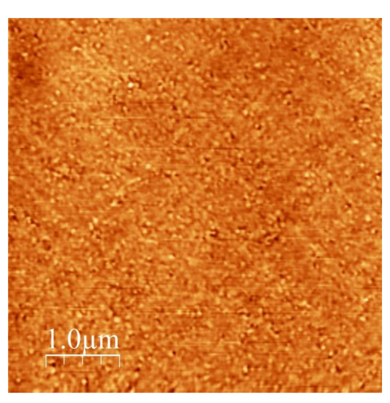
Lead Zirconate Titanate (PZT)

- Lead zirconate titanate is part of a class of materials called ferroelectrics. The titanium-rich phase has two stable configurations, each with nonzero out-of-plane (z-axis) polarization.
- When exposed to an electric field, ferroelectrics change their shape slightly, like piezoelectrics. When the field is strong enough, it can switch the configuration of the ferroelectric. This is the point known as the coercive field.
- Complex patterns of shapes with different polarizations arise, known as the ferroelectric domain structure.

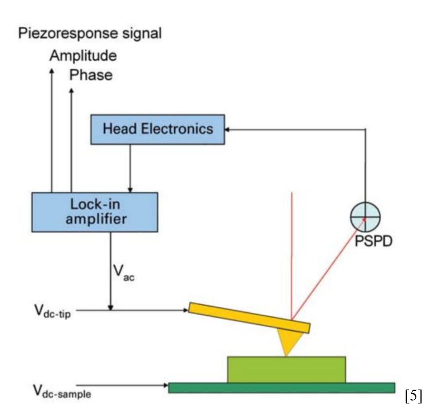




Piezoresponse Force Microscopy

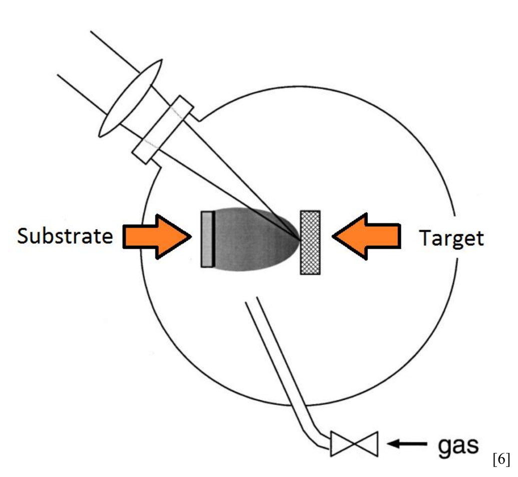


- An ultra-sharp tip attached to the end of a cantilever travels across the surface of the sample. The deflection of the cantilever is measured and corrected by observing the reflection of a laser onto a photodiode
- Line by line, an image of the sample topography is built up with nanometer resolution.
- A voltage can be applied across the sample to manipulate and observe ferroelectric domains.



Pulsed Laser Deposition

- A laser is used to ablate a target located in a vacuum chamber. The target material forms a plasma plume that spreads out through the chamber.
- When it reaches the substrate, the plasma cools and becomes incorporated into the substrate.
- PLD is known for its flexibility. It can be used to ablate almost any target, operate at a range of pulse frequencies and energies, and allows for the use of a reactive gas atmosphere.



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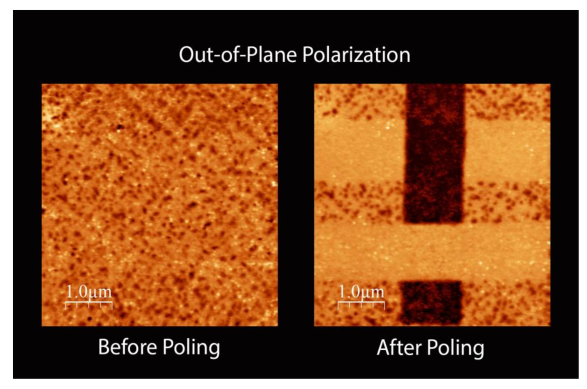
Methods

Fifteen samples of 20/80 lead zirconate titanate were prepared by pulsed laser deposition on substrates composed of lanthanum strontium manganite. The default growth parameters were 630ºC, 10 hertz pulse frequency, 3 minute growth time, and 100 millijoule laser energy. The parameters were varied individually, keeping all but one parameter at the default value for each sample. Samples were grown with pulse frequencies of 5 hertz and 20 hertz, with growth time adjusted to keep the number of pulses constant, at 600ºC, and with laser energies of 111 millijoules and 125 millijoules.



The samples were then analyzed by piezoresponse force microscopy. A 5µm by 5µm area was scanned to create a record of initial topography and existing ferroelectric domains. As illustrated in figure 1, a 9V DC bias was applied to a strip roughly 5µm by 1µm along the top of the initial scan area (a). A -9V bias was then applied to a 1µm by 5µm strip perpendicular to the first one. Finally, a 9V bias was applied to another 5µm by 1µm strip perpendicular to and overlapping the second. The sample was then scanned again to determine the effect of the poling. It was expected that a successfully grown sample of PZT should exhibit strong out of plane polarization, which would be evident from the contrast in the final scan. Additionally, it should show minimal surface disruption after poling. Samples which exhibited these behaviors were flagged for further investigation.

Results

The results of the study are summarized in the table to the right. The films grown under baseline conditions did not demonstrate substantial remnant polarization after exposure to an electric field. Furthermore, they showed major surface damage after such exposure, with raised portions in the poled regions persisting long after poling. Both of these characteristics indicate poor film quality. The films grown at a pulse frequency of 5 Hz showed evidence of ferroelectricity, but both of them also showed substantial surface damage.

Sample ID	Test Variable	Value	Ferroelectric	Surface Damage
150519A21	None	N/A	NO	YES
150519a4	None	N/A	NO	YES
150520a21	Pulse Freq.	5 Hz	YES	YES
150520a4	Pulse Freq.	5 Hz	YES	YES
150521A21	Pulse Freq.	20 Hz	NO	YES
150527A21	Laser Energy	125 mJ	YES	NO
150527A4	Laser Energy	125 mJ	YES	YES
150528A21	Laser Energy	111 mJ	YES	NO
150528A4	Laser Energy	111 mJ	YES	NO
150529A21	Substrate Temp.	600 C	YES	NO
150529A4	Substrate Temp.	600 C	YES	NO

The film grown at 20 Hz was found not to be ferroelectric and showed some surface damage. On the other hand, both films grown at 111 mJ and one film grown at 125 mJ laser pulse energy showed no major surface disruption after poling and demonstrated strong ferroelectric behavior. Both films grown at 600ºC also showed no signs of damage from exposure to the large electric fields and showed ferroelectric activity.

Future Steps

One goal of future work is to accurately measure the coercive voltage of the samples. Potential compositional variations across individual samples, as well as the effect of tip geometry on electric field strength inside the sample makes it difficult to determine from a basic PFM scan the exact value of coercive voltage. However, this can be done by creating a capacitor-like structure that can create a relatively uniform electric field inside the sample. Another place to improve upon this study would be in the volume of samples tested. It seems that 111 mJ laser energy is a promising value, so it would be desirable to produce many samples using that value in order to look more closely at sample-to-sample variations. Once issues of sample consistency and quality are ironed out, the next step would be to integrate a ferroelectric layer into an actual transistor and begin the process of shrinking down to nanometer scale.

Citations

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