

# **Quantum Computing Using Optical Waveguides Formed By Pulsed Laser Deposition and RF-Sputtering**

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## **Abstract:**

Thin films of Ta<sub>2</sub>O<sub>5</sub> were deposited on glass substrates using both pulsed laser deposition and RF-magnetron sputtering with a tantalum pentoxide target. The film thickness, roughness, transmittance, and extinction coefficient were measured for samples of both methods of deposition. The data taken from the thin films suggests that samples made via pulsed laser deposition are better suited for use as optical waveguides, due to their smaller RMS roughness.

## **Introduction:**

I have spent this summer using pulsed laser deposition (PLD) and radio frequency sputtering (RF-sputtering) to produce thin films of tantalum pentoxide. By etching gratings into the surface of the thin films and shining light through the gratings, optical waveguides can be produced. My group's project is to use these optical waveguides to form an optical lattice, the intensity pattern formed when two or more beams from a laser

are made to intersect. This planar lattice makes a 2-D trap (in the plane of the film), and by using certain modes of light, the atoms can be held at a certain distance above the surface, creating a 3-D trap of cold, neutral atoms. This 3-D trap enables each atom to be used as a qubit for quantum computing. My focus in this paper is on optical waveguides and my approach to making and analyzing thin films of tantalum pentoxide.

The modes of light that have been chosen to create the optical waveguides are the  $TE_0$  and  $TE_1$  modes. TE stands for transverse electric, which denotes that the electric field is traveling only in the direction of light propagation. The two smallest normal modes are used because they have the smallest extinction coefficients, which is an indicator of the loss of light as it travels through the film. Losses occur through three mechanisms: scattering, absorption, and radiation. Radiation losses are negligible in planar waveguides for well confined modes far from cutoff. Absorption, or bulk, losses are dependent on the material itself, but are negligible compared to scattering losses in amorphous thin films. Scattering losses are caused by volume scattering, defined as inconsistencies throughout the film (such as voids or contaminant atoms) and by surface scattering. Volume scattering is negligible compared to surface scattering. Surface scattering is dependent on the roughness of the surface and the number of interactions between the surface of the waveguide and the propagating wave.<sup>1</sup> To make an optical waveguide, a thin film made of an appropriate material must be used because the effectiveness of a waveguide is dependent on the properties of the thin film material.

Tantalum pentoxide has been identified as a material that is suitable for a number of applications in microelectronics due to its high dielectric constant, low dielectric loss, low leakage current, chemical and thermal stability, high refractive index, and high

transparency in the visible and soft UV range.<sup>2,3</sup> One such application of a tantalum pentoxide thin film is its use as an optical waveguide. Thin films are made by a variety of methods, including evaporation, sol-gel, chemical vapor deposition (CVD), pulsed laser deposition (PLD), and RF magnetron sputtering.<sup>4</sup> This paper reports the optical properties that result from the PLD and RF sputtering methods.

### **Experiment:**

#### 1. Pulsed Laser Deposition

A one inch diameter tantalum pentoxide disc was used as the target. It was cleaned prior to each use with sandpaper and acetone. Float glass was used as the primary substrate. It was cleaned before use ultrasonically with soap and water. The float glass was attached to the heater surface using silver paste. A microscope slide was used to cover part of the float glass, in order to have a distinct separation between film and glass. The chamber was pumped down below  $3.0 \times 10^{-6}$  Torr. The temperature of deposition ranged from room temperature to 150°C. 50°C was eventually chosen as the standard temperature. An oxygen pressure of 10 mTorr was used for all depositions. A KrF excimer laser ( $\lambda=248\text{nm}$ ) emitting 500mJ pulses was used to ablate the target. The pulse rate was varied from 5-25 Hz; 10 Hz was determined to give the best balance between speed (corresponding to a constant supply of energy) and smoothness of the surface. The number of pulses varied from 7000 to 97144. The plume formed by laser ablation was approximately two centimeters long, while the distance from the target to the substrate was approximately eight centimeters. The thickness of the samples was measured using a surface profiler, and the roughness was measured via AFM.

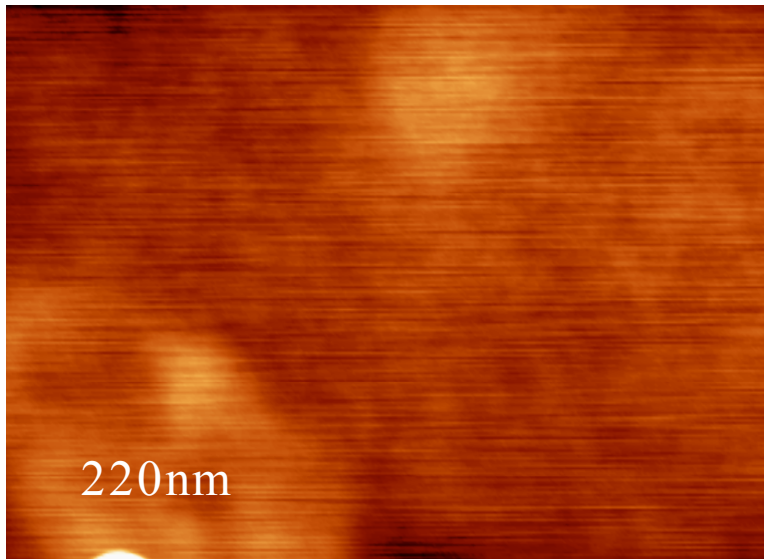
## 2. Sputtering

A two inch diameter tantalum pentoxide disc was used as the target. It was cleaned with acetone prior to use. Microscope glass (1 in x 1 in) was used as the substrate, cleaned ultrasonically with soap and water. The substrate was held in place by a metal clip. The chamber was pumped down below  $1.0 \times 10^{-7}$  Torr before 16.5 mTorr argon and 1.5 mTorr oxygen were added. A digital RF source (13.56 MHz) was used to maintain the Ar discharge. The thickness of the samples was measured using a surface profiler, and the roughness was measured using an AFM.

### **Results and Discussion:**

#### 1. Pulsed Laser Deposition

Samples made by PLD generally have a roughness  $< 5\text{\AA}$ , as shown in Figure 1.



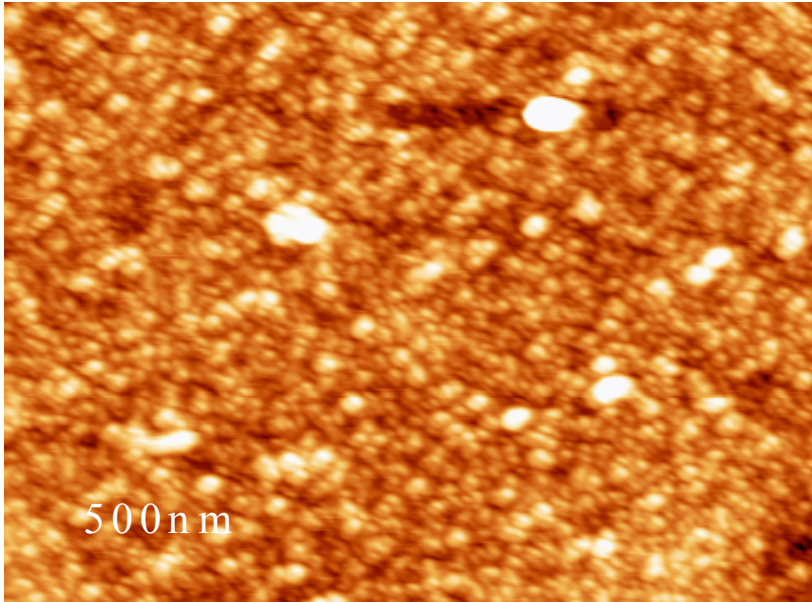
**Figure 1.** AFM scan of a sample made through pulsed laser deposition on float glass, with an RMS roughness of  $4.1013\text{\AA}$ .

The thickness of various samples ranged from 60 nm to 725 nm, which is partly due to varying the conditions of the experimental procedure. However, the results were neither predictable nor repeatable. While the deposition rate was influenced by temperature and pulse rate, these two properties do not account for the behavior of the deposition rate. In the same reaction conditions, doubling the number of pulses did not double the thickness of the film. The most likely cause for this data is that the target would become black after a certain number of pulses, causing the plume to decrease in size substantially. Therefore, the target would need to be cleaned after every 10000 pulses to maintain the same deposition rate.

The films were mostly transparent, but were still somewhat reflective. Tantalum pentoxide films should be almost completely reflective. Annealing the films improved the transparency. Measurements for the transmittance and absorption of the film will be underway in weeks to come, and will help determine the consistency and accuracy of the films.

## 2. RF Sputtering

Samples have a roughness  $> 20\text{\AA}$ , as shown in Figure 2, which is much greater than the roughness of samples made using PLD.



**Figure 2.** AFM scan of a sample made by RF-sputtering on microscope glass, with an RMS roughness of 28.3898Å.

The thickness of the sputtering samples is consistent around 300 nm, with a constant deposition rate. The sputtered films were more transparent than the PLD samples, but annealing did not improve the transparency. In fact, annealing caused the samples to become rougher, and caused a crystalline structure to form.

The difference in roughness and in response to annealing for samples made by the two different methods are probably due to the different substrates. Float glass has a roughness of 2-3 Å, whereas microscope glass has a roughness of 5-10 Å. This shows that the roughnesses are not necessarily comparable, but it does seem to suggest that PLD is still a better method to improve roughness; the roughness of PLD samples is similar to the roughness of float glass, while the roughness of sputtered samples is more than double the roughness of microscope glass. However, to prove this conjecture, the same kind of glass should be used in both setups to determine the roughness of each method on

the same substrate. Similarly, annealing the two different kinds of glass can have different effects. The softening point of microscope glass is much lower than that of float glass, and is approximately 600°C. This temperature was used because it is the optimum value for annealing tantalum pentoxide films.<sup>5</sup> However, it could have softened the microscope glass, resulting in changes in the properties of the film.

Optical waveguides have been made from both PLD and sputtered samples by etching gratings into the surface and coupling light by varying the angle of incidence of a laser beam. From this, preliminary measurements of the extinction coefficients (indicator of how much light is lost) have been made. For both PLD and sputtered samples, the extinction coefficient is approximately 8 dB/cm for the TE<sub>0</sub> mode. The expected value of the scattered losses, which should dominate for an amorphous tantalum pentoxide thin film, is less than 1 dB/cm. Also, since roughness determines the scattered losses, and the roughness of the sputtered samples are much greater than the roughness of the PLD samples, the losses must be bulk losses. An explanation for this unexpected behavior is that in both methods of deposition, the tantalum pentoxide is broken up during the process, and then re-formed on the substrate. In both cases, if the ambient oxygen pressure is not at the optimum value, tantalum metal could be deposited on the substrate as a result.

To counteract this effect, the oxygen pressure during deposition could be changed to find a pressure that will cause a more precise film to form. Another option that is currently being pursued is to anneal the samples for a longer time. Annealing the samples has been increasing the thickness of the film by about 50%, which means that the film is taking in more oxygen (indicating that it had been previously lacking oxygen).

However, annealing for 6 hours has increased the thickness by 100%, which suggests that two hours is not long enough. If the sample had not been annealed long enough, then tantalum would have contaminated the film, resulting in much greater bulk losses than expected. This would explain why the extinction coefficients for both methods were the same, even though the roughnesses were an order of magnitude different.

### **Conclusion:**

Before one method of deposition can be asserted as a better method to make optical waveguides, more data must be taken. The experimental procedure is currently underway to determine the extinction coefficients of thin films formed by each method which have been annealed for a longer time. Unfortunately, the data is still a week or two away, and time restrictions have forced this paper to be written without the data. My prediction is that the films produced using PLD will have a smaller extinction coefficient than those made using RF-sputtering, which would indicate that PLD is the method better suited to formation of optical waveguides. My prediction is supported by the fact that scattering losses are due primarily to surface roughness. Bulk losses are determined by the material, so the bulk losses of tantalum pentoxide thin films should be consistent whether PLD or RF-sputtering is used to deposit. Since RF-sputtering causes a greater roughness, the extinction coefficient should also be greater, corresponding to a less precise waveguide. The PLD setup is also more manageable, except that the thickness is not as easily controlled.

Before the waveguides can form the optical lattice to be used as a 3-D trap for quantum computing, the extinction coefficients must be brought down below 1 dB/cm. Pure tantalum pentoxide films would exhibit coefficients below this limit, so steps need

to be taken to improve the quality of the film. For these two methods, longer annealing times, different ambient oxygen (and argon) pressures, and slower pulse rates for PLD could possibly lead to more uniform samples.

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