

# Process Metrology for Ultrathin Gate Dielectrics

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**Abstract**— One of the major challenges is to be able to grow and accurately measure such thicknesses of gate oxides. In addition, the gate oxide thickness may change during the polysilicon deposition, which is important to measure from the device point of view. The use of variable angle spectroscopic ellipsometer (VASE) has been shown to provide a technique for directly measuring the thickness of the oxide underneath polysilicon.

The objective of this study is to use VASE (energy range from 0.78 eV to 6 eV, which corresponds to wavelengths from 200 to 1600 nm) to measure ultra thin silicon dioxide layers with and without polysilicon. Thin oxides have been grown under different experimental conditions in a furnace. The first set of wafers had only native oxide, the second set of wafers followed a five minutes soak, and the third one followed a ten minutes soak at 750 C in dry oxygen. A 430 nm polysilicon layer has been deposited on these wafers by low pressure chemical vapor deposition (LPCVD). To extract useful information, a model is constructed that describes the sample structure. It has been possible to measure thin oxides without the polysilicon. With polysilicon, however, problems are encountered. The optical constants change significantly with polysilicon processing conditions and the model must be adjusted to take into account these changes. The effective media approximation (EMA) is often used that describes mixing of two phases – crystalline and amorphous. After experiment, we found that something changed in the oxide during the polysilicon deposition. It can either be the thickness of this oxide, or some contaminants can be incorporated between the oxide and the polysilicon, changing the refractive index.

**Index Terms**— Airborne contamination, Ellipsometry, Polysilicon, Thin oxides, Wavelength.

## I. INTRODUCTION

IN the near future years, the size of the devices will continue to shrink, and this will go faster and faster. Consecutively, gate oxide thicknesses for the CMOS technology will dramatically shrink, maybe down to 15 nm according to the ITRS (International Technology Roadmap for Semiconductors) Roadmap. In order to grow accurate oxide thicknesses, and to be able to measure them, we have to find new ways of growing oxides. Indeed, new problems will be encountered, such

as Molecular Airborne Contamination (MAC) for example. This could lead to completely change the oxide thicknesses, and have completely different results, and performances of the devices.

In this paper, we are going to describe this problem, and propose a new method to anneal it. This method is based on a polysilicon deposition to avoid MAC contamination. We will also see that how we can accurately measure the oxide thickness underneath the polysilicon.

## II. THIN FILMS AND CONTAMINATION

As we already said, even a light contamination is very bad for thin films, due to the very small thickness, a very little change in this thickness can be huge compared to the original thickness of the film. Let's see where this contamination could come from.

The cleanroom, as clean as it can be, contains a very little amount of impurities that can be harmful for IC processing, such as dust, Na atoms, or impurities in water (deionized water), but contains organic molecules and compounds, for example due to the human presence, and the human breathing. These adsorbed contaminants appear to be organic compounds because they can be removed by rinsing with an oxidizing agent. While cleanroom air may be particulate-free, it can have higher levels of molecular organic contaminants than office environments because of volatile process chemicals used in the cleanroom, and because of the more frequent air circulation through organic filter media that is used to trap particulates. [1]

The air also contains 20 % O<sub>2</sub>, and 80 % N<sub>2</sub>, like "regular" air. These are the components of what we call the airborne contamination. Indeed, a wafer with very thin oxide exposed to such an environment can see an additional growth of oxide, or the oxide properties changed (thickness, refractive index). The old processes grew the oxide in a separate tool than the polysilicon growth. This induced that the wafers were in contact to the ambient in the cleanroom, allowing the absorption of Molecular Airborne Contaminants. These contaminants have been shown to have a negative effect on gate oxide integrity, and they are also known to cause the measured thickness of the gate oxide to increase over time. The

opportunity to grow both the gate oxide and the polysilicon in the same tool (same vacuum environment) allows to speed up the growth speed of both the oxide and the polysilicon, and avoids the deposition of MAC contaminants between the two layers.

### III. PROCESS CONTROL REQUIREMENTS

Precisely controlling the thickness of ultrathin gate dielectric film is critical for high-yield advanced-generation semiconductor manufacturing. [1]

One way to achieve more repeatable metrology measurements of gate oxide thickness is to clean the wafer immediately before every measurement. A fully effective cleaning procedure, whether chemical or thermal, must be carefully controlled and can take 5-15 min or more. Even then, very stable measurements are hard to achieve because the rate of apparent film growth is much faster (up to 0.1 nm/hr) immediately after cleaning. This can make the required repeatability of 0.006 nm (Data from the ITRS Roadmap) difficult or impossible to attain because this growth can place doubt in the accuracy of the measurements. In addition, cleaning some wafers to achieve stable metrology leaves the remaining wafers with organic contaminants that may have the potential to cause defects in the ultrathin oxide layer.

Many manufacturers are now fabricating polysilicon/SiO<sub>2</sub> gate structures using cluster tools that offer separate process chambers that are linked by an isolated vacuum chamber containing a robot that transfers wafers between chambers. These gate-stack cluster tools form both the gate dielectric and the polysilicon gate electrode without exposing the ultrathin gate oxide to MACs in the cleanroom environment.

In traditional batch processing, after the gate oxide is grown, the wafer may be stored for minutes, hours or even days before the polysilicon gate electrode is deposited in a separate processing tool. In addition to the problem of MAC adsorption during these holding times, both processing steps require handling of the wafers. Errors may result either from improper handling or improper processing. As an example, a batch of wafers may accidentally be put through the polysilicon deposition chamber twice. The double deposition of polysilicon requires the whole batch of wafers to be scrapped. In cluster tools, all the handling is done by robots, reducing the potential for human error. [1]

### IV. OXIDE GROWTH

In this section, I will explain how the oxide was grown for our experiment. We used the Bruce furnace to perform this growth, with a recipe that was already used in the RIT SMFL (Semiconductor and Microsystems

Fabrication Laboratory). The recipe was the following. The temperature was the same for all the wafers, and was fixed at 750 C in a dry O<sub>2</sub> ambient. We will fabricate three sets of wafers. One won't follow any treatment in the furnace, but will be exposed at the cleanroom's air, so will develop native oxide due to, as we said before, the O<sub>2</sub> ambient contained in the cleanroom's air. A second one will follow a five minutes soak with this recipe, and the last one will follow a ten minutes soak.

After that, polysilicon will be deposited using an LPCVD (Low Pressure Chemical Vapor Deposition) tool. During this step of the process, the gas that is used is Silane (SiH<sub>4</sub>), and the temperature is 600 C.

Let's see the treatment that we will do to the wafers that we'll use :

TABLE 1  
TREATMENT OF THE WAFERS.

Wafer ID	Oxide	Poly
1	Native	None
2	5 minutes	None
3	10 minutes	None
4	5 minutes	4300 Å
5	10 minutes	4300 Å

Thanks to the experiments that have been carried out before, we expect a thickness of 15 Å for the native oxide, 30 Å for the wafers that have followed a five minutes soak, and 40 Å for the wafers that have followed a ten minutes soak.

This knowledge of the expected results given by our recipe will allow us to see if our results are consistent, and to see if our measurement is meaningful or not.

Furthermore, the expected polysilicon thickness with the recipe we used to grow it is approximately 4300 Å.

### V. METROLOGY FOR ULTRATHIN OXIDES UNDER POLYSILICON

A good solution to measure such oxides is to measure the thickness underneath the transparent polysilicon. [1] Multi-wavelength laser ellipsometry and new algorithms developed at Rudolph Technologies make possible accurate and repeatable measurements of gate oxides as thin as 2.0 through ~150 nm of polysilicon. This method has the added benefit of simultaneously measuring the integrity of the entire gate structure. All measurements presented in this article were made using a Rudolph Technologies S200-ultra ellipsometer having multiple laser wavelengths, variable spot size and the ability to simultaneously acquire data at multiple angles of incidence. In our experiment, we

are going to use the J.A. Woollam VASE ellipsometer. (VASE = variable angle spectroscopic ellipsometer). This one has the following properties. The light provided has a wavelength range from 200 to 1600 nm, which corresponds to energies from 0.78 to 6 eV. Furthermore, the spot size is very small, which allows minimizing the error due to the spot. [2]  
A sketch of the ellipsometer is given appendix 1.

The light is randomly polarized when it goes out from the laser. The polarizer changes the polarization of the light and provides planar waves. The quarter-wave plate also changes the polarization of the light, and the beam becomes elliptically polarized. This elliptic light will go to the sample, and go deep into the polysilicon, depending on the wavelength of the light at the moment. After reflection, we will have once again planar waves, which will go through the analyzer and be detected or not by the detector. We will have a detected intensity that varies with the wavelength. Let's write down the intensity of the light in the detector :

$$E_i \rightarrow P \left[ \begin{array}{c} \lambda/4 \\ P_{//} \end{array} \right] \left[ \begin{array}{c} \lambda/4 \\ \lambda/4 \end{array} \right] \left[ \begin{array}{c} \text{Sample} \\ A_{//} \end{array} \right] A_{\perp} = R$$

We know everything here but the sample parameters. That's our unknown. Our ellipsometer will give us experimental values for  $\Delta$  and  $\Psi$ , which will be compared of theoretical values given by the model. These are directly linked to the Fresnel coefficients for the sample, which are themselves dependant on the refractive index of the different layers that are present on the wafer, the refractive index of the substrate, and the thicknesses of the layers. These are complex numbers, which are like :

$$R^* \exp(i\Delta)$$

where R is a real number proportional to  $\tan \Psi$ .

Then, we're going to see if the values (theoretical and experimental) match. If it is the case, the model will be able to extract the thickness of the oxide if we know all the other parameters (refractive index of the oxide, the polysilicon, and the substrate, and the thickness of the polysilicon).

If the values don't match so well, we will have to be careful before concluding, because the results will be maybe inaccurate.

A model is essential to be able to extract the data that we need from the ellipsometer measurements. This is true every time we use an ellipsometer. So, the accuracy of this model is essential to make our measurement meaningful. We are slaves of this model, and if the model that we use is inappropriate, we'll have to think about a new one to get better results.

## VI. RESULTS AND DISCUSSION

We got results from the model like presented in appendix 1 for each wafer. (fig. 2 and 3)

We can see that the results given by the model are consistent at short wavelengths, but not so much at longer wavelengths. This can be due to a lack of accuracy of the model. Indeed, maybe the model is more accurate at short wavelengths than at longer wavelengths.

Once again, we can say that our results are strongly dependant on the model.

To have a better idea of the accuracy of the model, let's take a look at the thicknesses given by the model when we enter the refractive index of the polysilicon, the oxide, the substrate, and the thickness of the polysilicon :

TABLE 2  
RESULTS OF THE MODEL.

Wafer ID	Oxide	Poly	Oxide thickness (Å)
1	Native	None	18.6 +- 0.3 Å
2	5 minutes	None	29.5 +- 0.2 Å
3	10 minutes	None	35 +- 0.1 Å
4	5 minutes	4300 Å	53 +- 23 Å
5	10 minutes	4300 Å	106 +- 27 Å

We can first note that the results are not consistent with and without polysilicon. This can be due to the problem of model, of which we talked before, or that can be a process problem. Indeed, we also note that the results with polysilicon are way farer from the "expected results" than the results obtained with the wafers that have no polysilicon on top. This could mean that the model is not so bad, but the wafers were "altered" while growing the polysilicon.

To explain that, we can make hypothesis on what's happening in the LPCVD tool. First, we can say that, even with a good vacuum in the tool, there are still oxygen atoms remaining. Let's calculate how many :

The base pressure for this tool is approximately 1E-2 Torr. This corresponds to 2E19 air molecules per cm<sup>3</sup>. But we know that there is 20 % O<sub>2</sub> in the air, so at the base pressure of the LPCVD tool, there would be approximately 6E18 O<sub>2</sub> atoms per cm<sup>3</sup>. At 600 C, this can be enough to grow some oxide on top of the thin oxide we grew in the Bruce Furnace.

So, maybe some more oxide is grown in addition to our thin oxide in the LPCVD tool.

Then, our wafers have been in contact with the cleanroom during their trip from the Bruce Furnace to the LPCVD tool. This has maybe led to incorporate in the oxide the MAC contaminants that we talked about before.

Indeed, incorporating contaminants in the fresh grown

thin oxide can change its optical and mechanical properties, such as the refractive index for example. That's what will have our interest here. To run the model that gives the corresponding thickness from the measurements of the  $\Delta$  and  $\Psi$  by the ellipsometer, we have to give the refractive index of the oxide and the polysilicon. But if the refractive index of the oxide changes, the model will give us false results, just because this parameter is not accurate.

So, maybe the refractive index of the oxide is changed by incorporation of the MAC contaminants, which leads to false modeled results.

#### VII. CONCLUSION

As a conclusion, we can first say that this ellipsometric system can work to measure thin oxide thicknesses, and maybe it works through polysilicon too. We can say that, because we had quite good results, compared to what we expected, when we measured the oxide thickness, even the native oxide, with no polysilicon on top. This is a good point. We can also say that, even if it's not very accurate, we managed to measure something with the polysilicon on top. This is a good point too, because maybe what we measured is the actual thickness of the oxide there was under the polysilicon (if some additional oxide has been grown in the LPCVD tool), or maybe the measurement is false due to a modification of the properties of the oxide (if there is incorporation of MAC contaminants between the oxide growth and the polysilicon growth). In both cases, the ellipsometer has measured something, and it's in the worst case only a matter of inadequate model. This is easy to fix.

So as a complementary work that can be done on this project, one can make other experiments in the LPCVD tool to see what's happening in there. For example, an experiment that can be done is to put a wafer with native oxide, which we know the thickness, and to see what is the wafer like after a run in the tool. This hasn't been done during the senior design, because of a lack of time. Maybe we will have results that match with what we got in this project with the polysilicon on top of the oxide on the wafers. In this case, we will be able to affirm that there is actually something happening in the LPCVD tool, and, even if we don't know accurately what, a big number of such runs will allow us to estimate, with the help of statistics, how much the results we get are inaccurate, and make the correction each time.

Another thing that can be done is to try not to put the wafers in contact with the cleanroom's air between the tools, and see how much this parameter is involved in the inaccuracy of our results. But this is less easy to carry out, and maybe it won't give us many interesting results.

#### APPENDIX

**Appendix 1 : Scheme of the ellipsometer VASE.**

**Appendix 2 : Results for wafer number 6 (5 minutes soak, no polysilicon on top).**

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