ANL/XFD/CP - 97499

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In situ Spectroscopic Ellipsometry as a Surface Sensitive Tool to Probe Thin Film Growth

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February 1999

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To be submitted to the International Conference on Metallurgical Coatings and Thin Films

*This work is supported by the U.S. Department of Energy, Basic Energy Sciences-Materials Sciences, under contract #W-31-109-ENG-38.

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ICMCTF'99 MANUSCRIPT COVER SHEET

(Author: Please type or print information BELOW SOLID LINE ONLY)

Type of Paper: 1999 ICMCTF Proceedings

Journal:

Paper Number:

Format:

Editor:

Title of Paper: *In situ* Spectroscopic Ellipsometry as a Surface Sensitive Tool to Probe Thin Film Growth

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Keywords (maximum of four): Spectroscopic ellipsometry, sputter deposition, thin films, growth mode

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Abstract

Sputtered thin film and multilayer x-ray mirrors are made routinely at the Advanced Photon Source (APS) for the APS users. Precise film growth control and characterization are very critical in fabricating high-quality x-ray mirrors. Film thickness calibrations are carried out using *in situ* and *ex situ* spectroscopic ellipsometry, interferometry, and x-ray scattering. To better understand the growth and optical properties of different thin film systems, we have carried out a systematic study of sputtered thin films of Au, Rh, Pt, Pd, Cu, and Cr, using *in situ* ellipsometry. Multiple data sets were obtained *in situ* for each film material with incremental thicknesses and were analyzed with their correlation in mind. We found that *in situ* spectroscopic ellipsometry as a surface-sensitive tool can also be used to probe the growth and morphology of the thin film system. This application of *in situ* spectroscopic ellipsometry for metal thin film systems will be discussed.

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1. INTRODUCTION

For thin film deposition, three different growth modes are possible. The film may grow smoothly, atomic layer by layer, or it may form three-dimensional islands, or it may first grow a smooth layer and then grow islands. How the film will grow in a certain system often depends on the surface property of the substrate, the film, and the substrate-film interface [1]. There is an enormous number of reports in the literature devoted to thin film growth using various surface-sensitive techniques. Most of the studies use films grown by molecular beam epitaxy (MBE), where the film growth is well controlled at the atomic level. Sputter deposition, on the other hand, is more energetic and much faster. The growth of sputtered films is difficult to study using surface-sensitive analytical techniques. The sputtered films may not have atomic layer-by-layer

growth, but they still have different growth modes, such as smooth growth, island growth, and island formation after a smooth growth. Or we may simply use the film roughness to represent the film growth. It is important to understand the growth of sputtered films. For example, in x-ray optics, we need to control the film roughness in order to obtain a high reflectivity [2]. In the present study, we demonstrate that *in situ* spectroscopic ellipsometry can be used to probe the growth of metal thin films on a single crystal Si (100) wafer.

Spectroscopic ellipsometry has been widely used in thin film characterization in recent years [3-8]. The rapid progress is attributed to the advance of computer technology and readily available software for complicated model calculations. The technique is very sensitive. When used *in situ*, it should be able to detect subtle changes in the growth of the thin film. However, ellipsometry itself is an indirect measurement technique. The correct interpretation of measured data relies on theoretical model fittings with accurate sample structure and corresponding optical constants. For this reason, a systematic study on a series of systems is very helpful, and important information can often be obtained on a comparison basis.

In a previous paper [9] we carried out a systematic study of thickness and optical constant measurements of sputtered thin films of Au, Pt, Pd, Rh, Cr, Cu, as well as W and C, grown on Si wafers or glass substrates, using *in situ* ellipsometry. Incremental depositions with an equal amount of material dose were used for each element so that the linearity of the measured thicknesses could be checked. At first, we used a common practice in ellipsometry and assumed that the films were flat and parallel to the substrate and used the optical constants from optically thick films in the fitting. The measured thickness results were then compared with those obtained from interferometry and x-ray scattering measurements. In most cases, results from these three independent techniques agreed well with each other within 10%. The measured thicknesses of incrementally deposited films also formed a straight line on a scaled plot for most elements. These results indicated that ellipsometry can be successfully used to measure thin film thickness using this common practice. We found also however that in some cases a large error may result, especially in very thin (< 10 nm) films and in cases where the films are very rough. The optical constants of the thin films in general are different than those of optically thick films and that of the

bulk. Using *in situ* ellipsometry measurements, we discovered a relaxation effect in a Rh/Si film in vacuum two hours after the film was grown. By fitting the data with a rough-film model, we were able to explain that this relaxation effect was due to a roughening of the Rh film.

In the present paper we explore further the issue of film growth using incremental depositions and *in situ* ellipsometry measurements. We found that incremental deposition is powerful technique for systematic studies. Modern technology can easily control the thickness error in each incremental deposition to within 1-2 %. We thus have very high confidence in the thickness linearity of incrementally deposited films. This technique has been successfully applied by one of us to discover the two-dimensional magnetic properties of ultrathin MBE films of Fe [10, 11]. We now apply it in *in situ* ellipsometry applications. We are going to present four case studies to demonstrate that *in situ* ellipsometry as a surface-sensitive tool can be used to probe the growth of thin metal films. First, we represent results from our previous study of Au, Rh, Pt, Pd, Cu, and Cr on Si to show that there are differences in the growth mode in these systems. Then we reveal the possible smooth growth of thin Cr/Si films and rough growth of thick Cr/Si films by using model fittings. Finally we demonstrate that Au and Rh can grow relative smoothly on thin Cr/Si, and Rh grows quite rough on thick Cr/Si films. These four examples demonstrate that self-consistent conclusions can be obtained by using *in situ* ellipsometry alone.

2. EXPERIMENT

The thin films used for this study were made by DC magnetron sputtering in our deposition facility, which consists of four large vacuum chambers, each 16 inches in diameter and 66 inches long. Three CTI model CT-8 cryo pumps and an Alcatel ADP 81 dry pump provide a base pressure of $< 2 \times 10^{-8}$ Torr for the system. Samples on a sample holder can be loaded into a carrier, which can be moved from chamber to chamber by a computer-controlled transport system. Four 3-inch-diameter magnetron sputter guns are deployed in the deposition chamber. During the deposition, the substrates are usually moving. Uniform deposition can be achieved through the design of a shaped aperture over the sputter gun. *In situ* ellipsometry measurements were carried out in the measurement chamber, where two 4.5-inch ports provide a pathway for the light on a

sample at an incident angle of 80 degrees. The ellipsometer was a M-44 Ellipsometer made by J. A. Woollam Co., Inc. [12]. A detailed description of this facility can be found elsewhere [9].

The depositions were carried out at ambient temperatures and at an Ar pressure of 2.3 mTorr for all the samples reported here. Commercial 2-inch-diameter single crystal Si (100) wafers were used as substrates. These Si wafer substrates were flat and smooth, with a surface roughness of ~0.3 to 0.5 nm (root-mean-square value). Au, Rh, Pt, Pd, Cu, and Cr thin films on Si samples were made at incremental thicknesses up to a few tens of a nm thick, under identical growth conditions. Additional deposition up to a total of ~100 nm was then added to make an optically thick film for each material.

A 4" Si wafer with a ~25-nm-thick thermal oxide layer was loaded on the same sample holder for calibration purposes. Calibration was done for each set of measurements. Ellipsometry measurements were carried out before and after each deposition. Care was taken to make sure that the substrate was held flat and steady. A half-inch-thick cast aluminum substrate holder was used. Measurements after each deposition were done on the same spot on the sample. The elapsed time between the deposition and the measurement was typically less than two minutes. The ellipsometry data were later analyzed using the manufacturer's software.

To study the role of Cr as a "glue" layer [1] to the growth of Au and Rh, a thin film of Cr of ~6 nm was grown on Si followed by an incremental growth of Au (Rh), and *in situ* ellipsometry measurements were repeated. A thick Cr film of ~100 nm was also grown on Si before Rh growth for Rh on thick-Cr-film studies. The ellipsometer measurements were carried out as soon as the Rh film was grown to avoid the relaxation effect of the Rh film, which we have reported in an earlier paper [9].

3. RESULTS AND DISCUSSION

A. Difference in growth mode as indicated from traditional thickness measurements for incremental depositions of Au, Rh, Pd, Pt, Cr, and Cu

A common practice of thickness measurements in ellipsometry is simply to use measured optical constants of an optically thick film for corresponding thin film measurements assuming

that both the film and the substrate are flat and parallel to each other. Figure 1 shows the results for such a practice of *in situ* ellipsometer thickness measurements for Au, Rh, Pd, Pt, Cr, and Cu at the indicated nominal thickness. The nominal thickness was determined by scaling the speed of the substrate passing over the sputtering target according to previous growth rate calibrations. The number of passes at the same speed was then used to determine the nominal thickness after each deposition. The nominal thickness thus serves as a scale of the material dose on the substrate. The measured thickness was determined through model fittings of the ellipsometer data. The model consists of the thin film layer to be measured, a SiO_2 layer representing the native oxide on the Si wafer, and a pure Si substrate. These layers are assumed flat and the model is called "flat-film model". The thickness of the native oxide layer was fixed at the value obtained from the ellipsometry measurement on the substrate prior to the thin film deposition. The optical constants of SiO_2 and Si are in the manufacturer's database. Optical constants obtained from optically thick films were used for the deposited film. The film thickness and the angle of incidence were fitting parameters. Regression results indicated that the angle of incidence of the light beam was indeed in the neighborhood of 80° for all measurements, as expected from the vacuum port design. In most cases, we set the angle as a fitting parameter, because the exact angle of incidence for each sample is somewhat uncertain. The mean square error (MSE) is the sum of the squares of the differences between the measured and calculated data, with each difference weighted by the standard deviation of that measured data point. It indicates the quality of the fit, with lower values indicating better fits. The MSE values for each measurement are shown in Figure 1, using the scale on the right side of the figure.

From Figure 1, one can see that in general (except for Cr/Si) the measured thicknesses are aligned in a straight line, as one would expect for incrementally deposited films in a scaled plot. These lines also roughly extrapolate to zero thickness. One can thus conclude that the optical constants obtained from an optically thick film can be used to measure the thickness of thinner films with reasonable accuracy for most systems. Looking more carefully however, one can see that there are noticeable differences for each system, especially for the Cr/Si system. For the Cr/Si system, the measured thicknesses for films thicker than 20-nm nominal thickness are

obviously wrong because they are far below the expected values from a straight-line extrapolation. Another remarkable difference is that the trend of MSE values for the Cr/Si system is opposite to the behavior of other systems shown in Fig. 1. For the Cr/Si system, the MSE values increased with the film thickness, from 5.2 at ~3 nm to over 30 at 30 nm. For other systems, the MSE values decreased with the film thickness. A large MSE value indicates that the real film is not flat and smooth as assumed in the model. We thus suspect that Au, Rh, Pt, and Pd thin films in the range of <10 nm and Cr films thicker than 10 nm are rougher than other films. We know that Cr can form covalent bonds to SiO_2, by breaking the O-Si bond. Other metals, such as Au and Rh, have a poor adhesion on SiO_2. It is likely that Cr may grow more smoothly at the beginning because of the attraction of oxygen in the native oxide on the Si wafer. An island growth may follow afterwards. It has been observed through x-ray scattering measurements that Cr films have a tendency to become rougher as they grow thicker [13]. For other metal/Si systems, metal islands may form at the start of deposition and the films may become relatively smoother as more and more atoms are built up. By examining the MSE values in the thickness range of <5 nm for all six metal/Si systems, we noticed that metals with a higher chemical bond strength with oxygen (such as Cr) have a smaller MSE value. Au has a weak bond with oxygen, and we find large MSE values. Cu has a modest bond with oxygen, and we find medium MSE values. This observation is similar to that of Karnowsky and Estill in their adhesion measurements for metal/oxide systems, in which they found that Cr had the strongest adhesion, Au the weakest, and Cu in between [14].

As shown in Fig. 1, in addition to large MSE values, the measured thickness values for Cr/Si films thicker than 20 nm are lower than one would expect for the case of incremental depositions. In the next section, we demonstrate that more reasonable fit can be obtained by using a model with an added roughness layer and better optical constants.

B. Model-fitting of Cr/Si data with an added roughness layer and better optical constants

The roughness in the film can be modeled as an additional surface layer, referred as the "surface rough layer", which consists of the film material and voids. The optical constants of the

"rough layer" are calculated from that of the film material according to its composition by using the effective medium approximation [15, 16]. The model then consists of a Si substrate, a native oxide layer, a flat Cr layer, and a surface rough layer. The thicknesses of the flat Cr layer and the rough layer and the percentage of composition together with the angle of incidence are treated as fitting parameters. To simplify the matter, we can assume that we have equal amount of film material and voids, i. e., fix the composition at 50/50. One important criterion for a fit to be successful is that the total effective thickness (flat film thickness plus the percentage of rough layer thickness) for each film should scale according to the corresponding nominal thickness. Model fittings using this method have been carried out. However, when we used the optical constants extracted from an optically thick Cr film for the fitting, we could not get satisfactory fits for films thicker than 10 nm. Not only were the MSE values still too high (from 12 to 18), but also the effective thicknesses obtained from the fits were lower than one would expect (similar to that for Cr shown in Fig. 1).

When we use an optically thick film to extract optical constants, we have assumed that the film is flat and parallel to the substrate surface. For Cr/Si, however, as we argued before, the thick Cr film may be quite rough. Then the extracted optical constants will not truly represent that of Cr. Since we believe that when Cr is grown on Si, the first few layers will grow more smoothly, we may be able to obtain better optical constants from the thinner Cr films. To obtain optical constants from a single set of thin film data, we need to know the thickness of the film, which is difficult. However, by using multiple data sets one may overcome this problem [8, 9, 15]. To do this, we chose the first three data sets of Cr/Si (cf. Fig. 1) and assumed that the optical constants for these three thin Cr films are the same. We also assumed that these films are flat and parallel to the substrate surface. The model consists of a Si substrate, a native oxide layer, and a flat Cr layer, all coupled together for these three Cr films. Then it is a simple matter to use the manufacturer's software to group these three data sets together and obtain the optical constants and the thicknesses of the Cr films simultaneously. The optical constants so obtained can be found in an earlier publication [9]. We now use these optical constants to fit the Cr data using the rough-film model that we mentioned earlier. The model consists of a Si layer, a native oxide layer, and a

flat Cr layer, and a surface rough layer with half Cr and half voids. The thicknesses of the flat Cr layer and the rough layer and the angle of incidence are fitting parameters. This time excellent results were obtained, as shown in Fig. 2. Not only are the MSE values very low, but also the measured thicknesses for thicker Cr films are more reasonable for incremental depositions. The measured thickness is the sum of the flat Cr layer thickness and half of the rough layer thickness, as we assumed in the model. The rough layer thicknesses (not shown) range from 1.4 to 1.8 nm for films thicker than 15 nm. For the first three films, we have assumed that the films have no roughness in order to obtain the Cr optical constants and expect no roughness in the fitting results. We notice that there is a kink between the third and the fourth data points in the thickness curve of Fig. 2. This difference is caused by the different assumptions we made for the two parts of the data: no roughness in the first three films and rough for the others. But overall, the errors are small and the fittings are good. Apparently the optical constants we obtained from multiple thin film Cr/Si data ("thin Cr optical constants") worked better for the Cr/Si system.

C. Au and Rh films grown on thin-Cr-coated Si wafers

Here we demonstrate the effect of a thin Cr film as a "glue layer" on the growth of Au and Rh. A thin Cr film of ~6 nm was grown on a Si (100) wafer and measured with the *in situ* ellipsometer. Incremental deposition of Au and ellipsometry measurements after each deposition were then carried out, just as we did for the Au/Si experiment. This procedure was also repeated for Rh.

A flat-film model with no roughness was used to analyze the data. The model consists of a Si substrate, a native oxide layer with known thickness, a Cr layer with "thin Cr optical constants" and known thickness, and a Au (Rh) layer with "thick film" optical constants. The Au (Rh) layer thickness and the angle of incidence are fitting parameter.

Figure 3 shows the results of measured thickness and MSE values for Au and Rh as a function of nominal thickness. The fittings are very impressive. The MSE numbers are small, and the measured thickness values fall onto a well-defined straight line, as shown in the figure. The results clearly demonstrate that, when a thin layer of Cr (6 nm in the present case) is used as a "glue" layer, the subsequent Au (Rh) depositions are reasonably flat and no roughness layer is

needed in the model fitting of the ellipsometry data. When a thicker Cr film is used as a "glue layer" however, the situation is different, as shown next for the Rh on thick Cr on Si experiment.

D. Rh films grown on thick-Cr-coated Si wafers

For this experiment, a thick Cr film (~100 nm) was grown on a Si (100) wafer as the substrate for later Rh deposition. *In situ* ellipsometry data were taken for this thick Cr/Si film. To compare results of different model fittings, we repeated the two approaches described earlier to treat this film. The first one was to use the flat-film model to obtain the optical constants of this thick film, we call these optical constants as "thick Cr optical constants". The second one was to use the rough-film model to analyze the film, resulting in a thickness of 5.3 nm with a Cr composition of 75.2% for the surface rough layer. The fitting was good with a MSE of 6.5. The results of this fitting will be used in a later calculation. Incremental Rh depositions were carried out on this thick Cr film, and ellipsometry data were taken at every step of the process. We then used two different models to fit these same data of Rh on thick Cr.

(a). Flat-film model with "thick Cr optical constants"

In this model, the thick Cr film was used as substrate with "thick Cr optical constants". The "thick Cr optical constants" were directly extracted from the *in situ* ellipsometer measurement of this thick Cr film using a flat-film model. The Rh layer was assumed flat and parallel to the substrate. The Rh optical constants were obtained from a thick Rh film using a flat-film model. The thickness and the angle of incidence are fitting parameters.

(b). Rough-film model with "thin Cr optical constants"

In this model, we assume:

1). A flat Cr film of 100 nm thick with "thin Cr optical constants';

2). An interface rough layer 5.3 nm thick with a fixed percentage of 75.2% of Cr and the rest of Rh; (Note that the surface rough layer of the thick Cr film now becomes the interface rough layer in the Rh/Cr system, with Rh atoms replacing the voids.)

3). A flat Rh layer with optical constants obtained from a thick Rh film using a flat-film model;

4). A surface rough layer of a certain percentage of Rh and the rest of voids.

A schematic diagram of this model is shown in Fig. 4. In the interface rough layer, the thickness and percentage parameters are fixed at the values we obtained from model fittings we carried out for the thick Cr film, as we mentioned earlier. The thickness of the flat Rh layer, the thickness of the surface rough layer and the percentage number in the surface rough layer, and the angle of incidence, are fitting parameters.

Different results are obtained for the same data of Rh on thick Cr, as shown in Figure 5. Fig. 5a shows the measured Rh thickness and the mean square errors for each incremental Rh film plotted as a function of nominal thickness using the flat-film model. Fig. 5b shows results obtained from the rough-film model. In Fig. 5b, the measured thickness consists of three parts: effective thickness of Rh in the interface rough layer (24.8% times 5.3 nm), the measured flat Rh thickness, and the effective Rh thickness in the surface rough layer. From Fig. 5a one can see that the flat-film model does not work for the case of Rh grown on thick Cr films. Although the MSE values are reasonable, the measured thicknesses are far from a straight line in the plot. For example, while the measured thickness for the first film is close to the nominal thickness, the measured thickness for the last film is 26% higher than expected. In this case, the rough-film model works much better. Not only the MSE values are very small, but also the measured thicknesses are very close to what we would expect for incremental depositions.

Figure 6 shows experimental ellipsometry data for the two different model fittings of one of the Rh on thick Cr films. The experimental data, Ψ and Δ, are called ellipsometer parameters, which are directly obtained from the measurement [15]. Fig. 6a shows fittings using the flat-film model with a MSE value of 10.4, and Fig. 6b shows fittings using a rough-film model with a MSE value of 0.74. The difference in the quality of the fittings is apparent. A flat-film model is simply wrong for thick Cr films on Si wafers, as we demonstrated earlier. Here we confirmed again that, when thin films of Rh are grown on this thick Cr film, the Rh films would be rough as well. Also, by playing with model fittings, we found again that the "thin Cr optical constants" are much better than the "thick Cr optical constants" for the "flat Cr layer" in the rough-film model. For the Rh layer, the thick-film optical constants are fine. The Rh films may be smoother as they

grow thicker. This is indicated by the thickness numbers of the surface rough layer that we obtained from the model fitting.

Figure 7 shows the results of the rough-film model fittings for the surface rough layer (cf. Fig. 4) of Rh. The resulting rough layer thickness and the void percentage for each Rh film are plotted as a function of the nominal thickness. It is of interest to note that as the Rh films become thicker, the rough layer thickness gets smaller and smaller. The percentage of voids also decreases slightly. For the first two Rh films, the surface rough layer is almost as thick as the whole Rh nominal thickness. As the Rh film grows thicker, not only the relative but also the absolute value of the rough layer comes down. The thickness of the surface rough layer for a nominal 22 nm film is even smaller than that for a nominal 2.2 nm film (1.46 nm vs. 2.08 nm). This result indicates that, while the Cr film grows rougher with thickness, the Rh film becomes smoother. It may explain why the "thin Cr optical constants" are better for "flat" Cr layers while the "thick Rh optical constants" are fine in the model.

As a final note for the rough-film model, we found that this model does not work for very thin films, because of the correlation problem between fitting parameters. For example, although we suspect that for the Rh (or Au) on Si system the initial growth of the film is not smooth, we could not obtain a good fit using the rough-film model. The parameter correlation is expressed in terms of a set of two-parameter correlation coefficients and can be found in the sensitivity correlation matrix (available in the manufacturer's software) after a fit is completed. For very thin films, the total thickness is already very small. When the film is further divided into a flat part and a rough part in the rough-film model, the thickness parameters of two parts will inevitably correlate very strongly with each other. We found that this is indeed the case when we applied the rough-film model to fit the very thin Rh/Si (or Au/Si) films. For one thing, in the sensitivity correlation matrix the correlation between parameters was very high (as high as 0.996, for example). Also the uncertainty of the thickness value was unreasonably high. Both indicate a strong parameter correlation. This parameter correlation problem is well documented in the manufacturer's manual [15]. Fortunately we did not have serious correlation problem in the fitting of Rh on thick Cr data. For the Rh on thin Cr data, the flat-film model worked better than

the rough-film model. Although we do not expect perfect results, our experiments demonstrate that the present *in situ* spectroscopic ellipsometry technology can be used as a sensitive tool to probe the thin film growth in certain systems. The technique can help us to search for better thin film systems. For example, when we use Cr as a "glue" layer for metal/oxide deposition, now we know that a thin Cr film (< 10 nm) is better than a thick one in order to obtain a smooth metal film.

4. SUMMARY

In situ spectroscopic ellipsometry has been applied to study the growth and to measure the thickness of metal thin films. Extensive experiments of incremental film-growth coupled with *in situ* ellipsometry studies have been carried out for Au, Rh, Pt, Pd, Cu, and Cr on Si (100) systems. The thickness information of most thin metal films we studied can be obtained with reasonable accuracy from ellipsometry measurements using a flat-film model with optical constants of optically thick films. For the Cr/Si system we found that the initial Cr growth is smooth and the film becomes rougher as it grows thicker. The conventional flat-film model with thick Cr optical constants does not work for the Cr/Si system. Instead, a rough-film model with "thin Cr optical constants" worked well and revealed that thick Cr films were rough. Further experiments and modeling of Au and Rh grown on thin Cr films confirmed that thin Cr films and subsequent Au (Rh) films are reasonably flat and can be fit with flat-film models. Rh layers on a thick Cr film, however, are rough. But the surface roughness level decreases as the Rh film grows thicker. When Cr is used as a "glue" layer in metal on oxide systems, it is better to use a thin (< 10 nm) Cr film in order to obtain a smooth metal film. By using incremental deposition techniques and extensive modeling of the ellipsometry data on a series of metal/Si systems, we have demonstrated that *in situ* spectroscopic ellipsometry can be used to probe the film growth of thin metal/Si systems.

ACKNOWLEDGMENT

We thank L. Assoufid and P. Her for help in TOPO measurements, S. Krasnicki and J. Maj in x-ray measurements and R. Hopf for maintenance of the deposition facility. We are grateful to J. A. Woollam Company for technical support and helpful discussions. This work is supported by the U. S. Department of Energy BES Materials Science under contract W-31-109-ENG-38.

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FIGURE CAPTIONS

Fig. 1 Measured thickness (left vertical axis) and the mean square error (right vertical axis) plotted as a function of nominal thickness for incremental thin films of Au, Rh, Pt, Pd, Cu, and Cr grown on Si wafers. The data were obtained from fittings of spectroscopic ellipsometry data using a flat-film model. Optical constants obtained from optically thick films were used in the fitting, as described in the text. The nominal thickness is the targeted thickness of each accumulated incremental deposition according to a predetermined growth rate. The lines through data points serve as a guide to the eye. Error bars are smaller than the size of data marks. Note the significantly lower than expected measured thickness and the increasing MSE values for the thicker Cr films.

Fig. 2 Measured thickness and the mean square error plotted as a function of nominal thickness for incremental thin films of Cr grown on a Si wafer. The data were obtained from fittings of spectroscopic ellipsometry data using a rough-film model. "Thin Cr optical constants" were used in the fitting, as described in the text. The first three thin Cr films are assumed flat and parallel to the substrate. The other Cr films are assumed rough with a surface rough layer of 50% Cr and 50% voids. The measured thickness is the sum of the flat part and 50% of the surface-rough-layer part of the Cr film.

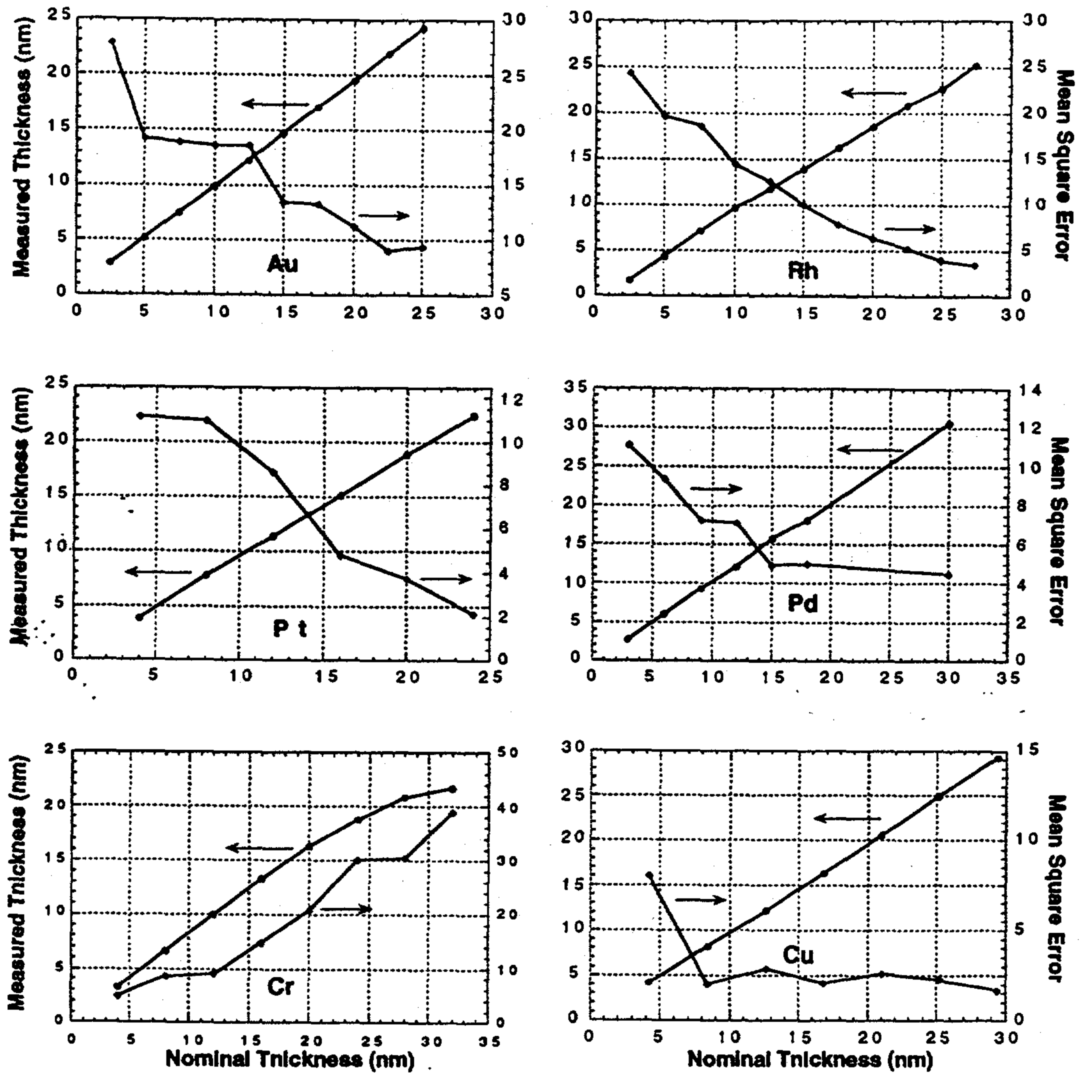
Fig. 3 Measured thickness and the mean square error plotted as a function of nominal thickness for incremental thin films of Au (and Rh) grown on a thin (~6 nm) Cr film on a Si wafer. The data were obtained from fittings of spectroscopic ellipsometry data using a flat-film model. Optical constants for Au (and Rh) obtained from optically thick films and "thin Cr optical constants" were used in the fitting, as described in the text.

Fig. 4 A schematic of a rough-film model for Rh on thick Cr. The interface rough layer consists of 75.2% of Cr and the rest of Rh. The surface rough layer consists of certain percentage of Rh and the rest of voids.

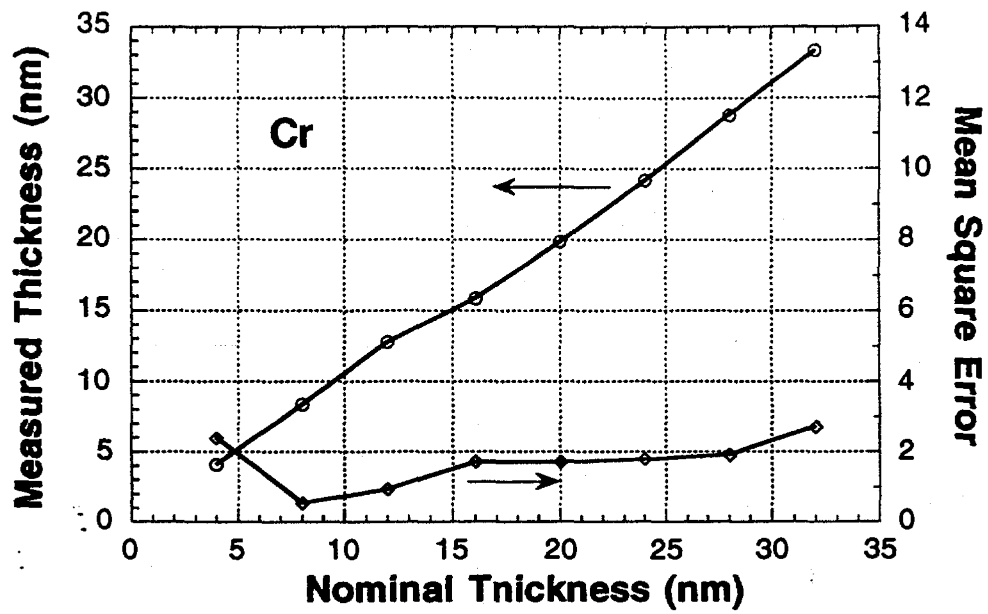
Fig. 5 Measured thickness and the mean square error plotted as a function of nominal thickness for incremental thin films of Rh grown on a thick Cr film using two different model fittings: (a) a flat-film model and (b) a rough-film model, as described in the text.

Fig. 6 Experimental ellipsometry data, Ψ and Δ (in degrees), of one of the Rh on thick Cr films along with the fitting curves from two different models: (a) a flat-film model and (b) a rough-film model, as described in the text. Note the difference in the quality of the fitting.

Fig. 7 Results of the rough-film model fittings for the surface rough layer of Rh (cf. Fig. 4). The resulting thickness and the void percentage of the surface rough layer for each Rh film are plotted as a function of the nominal thickness.



Liu, figure 1



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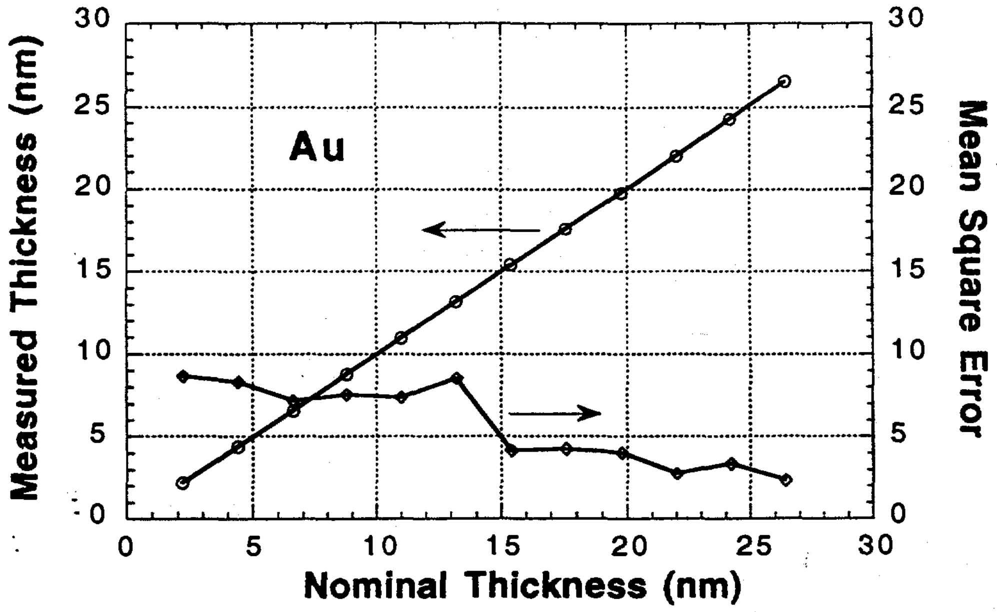

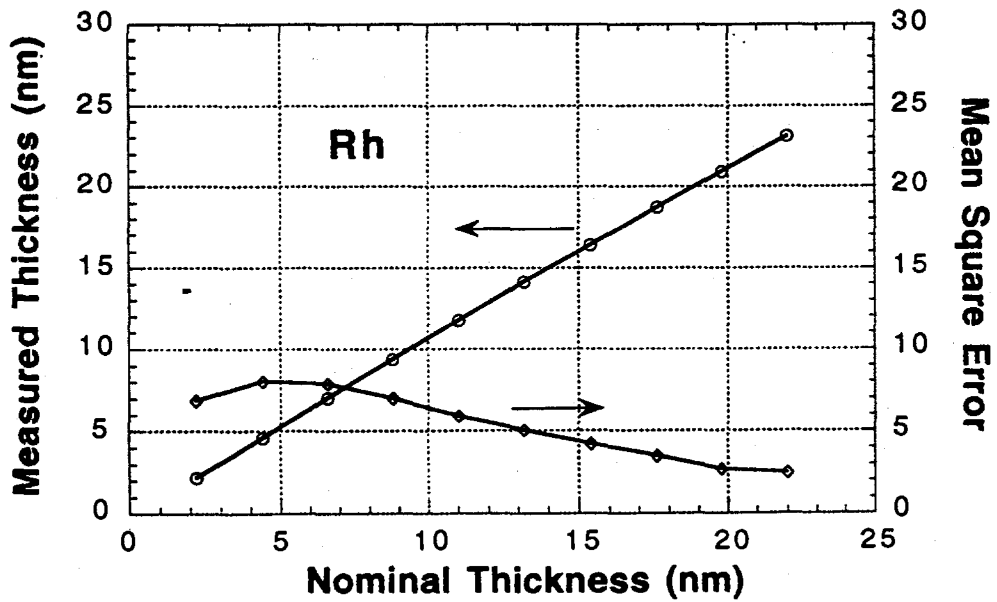

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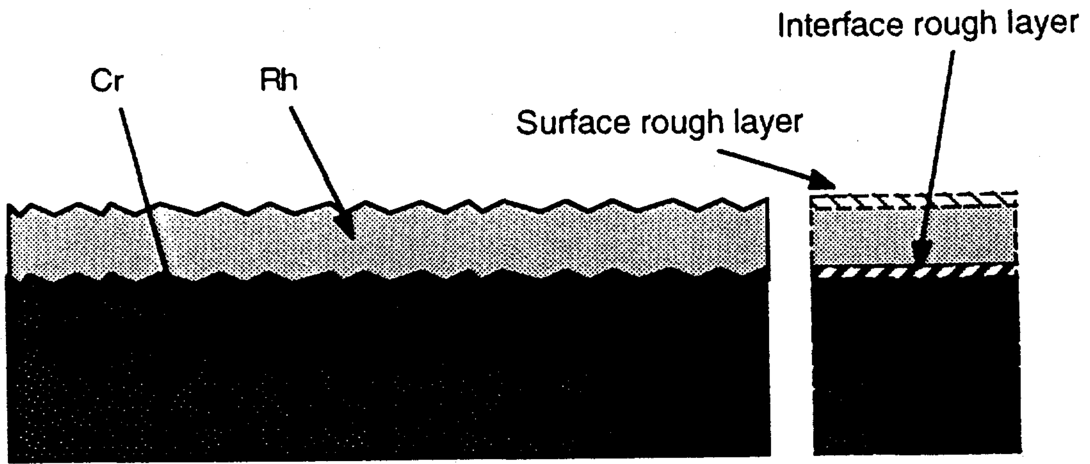

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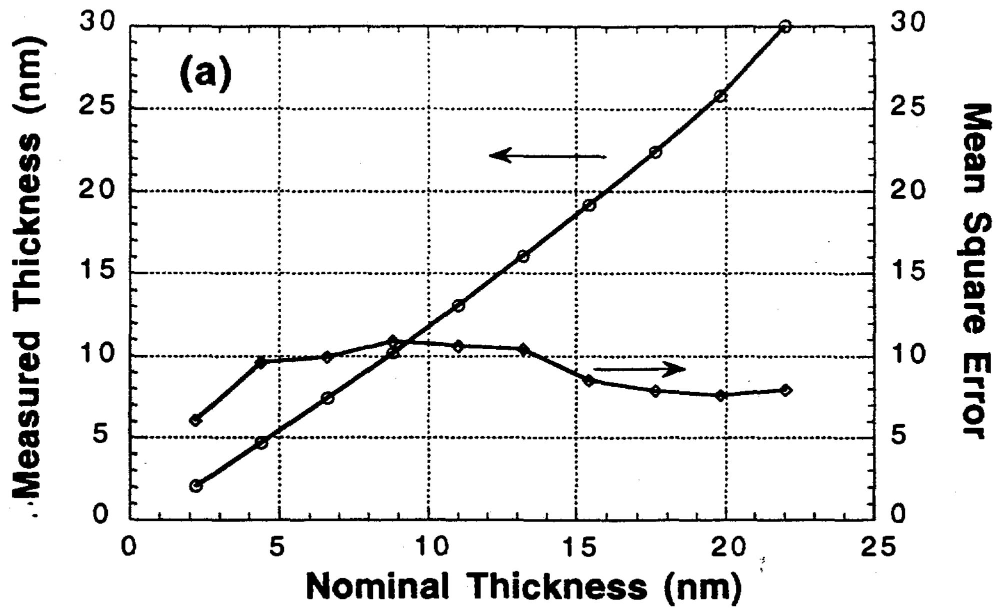

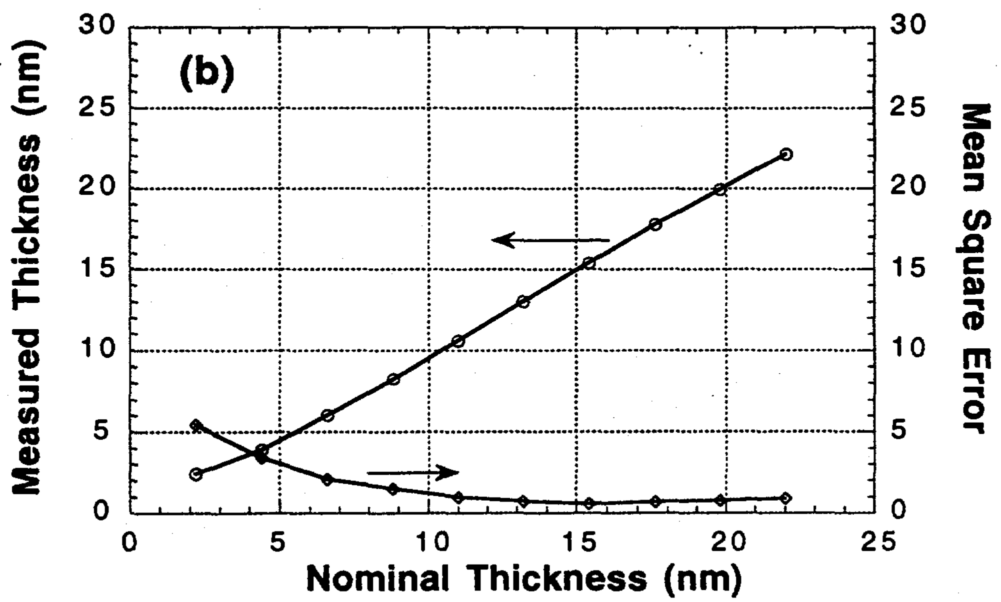

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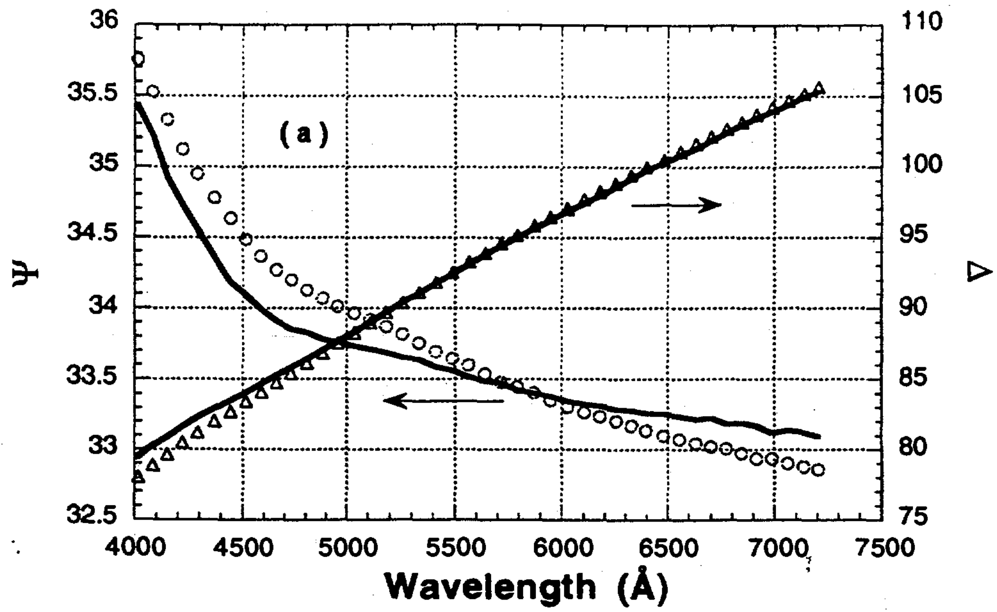
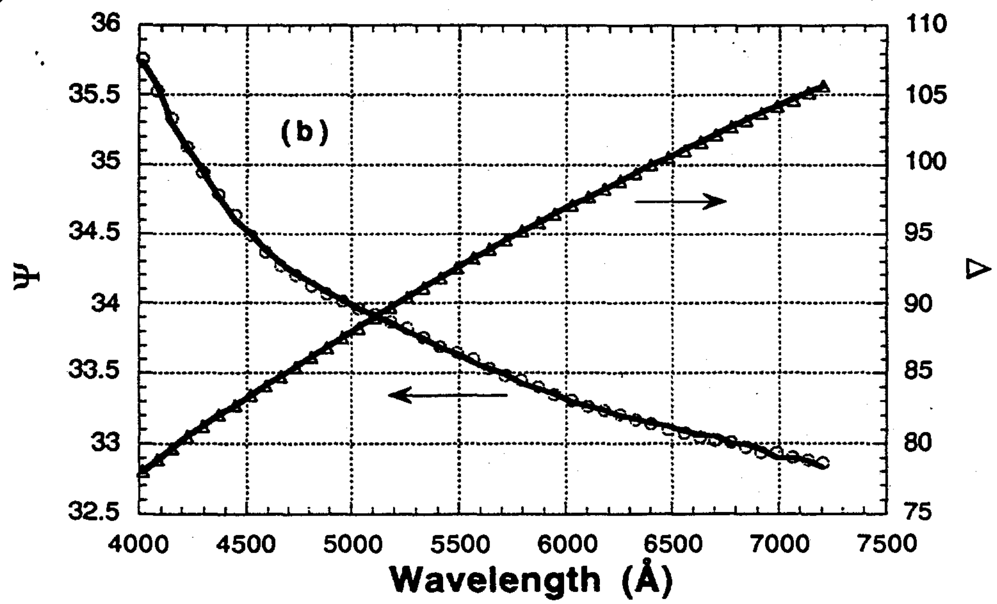
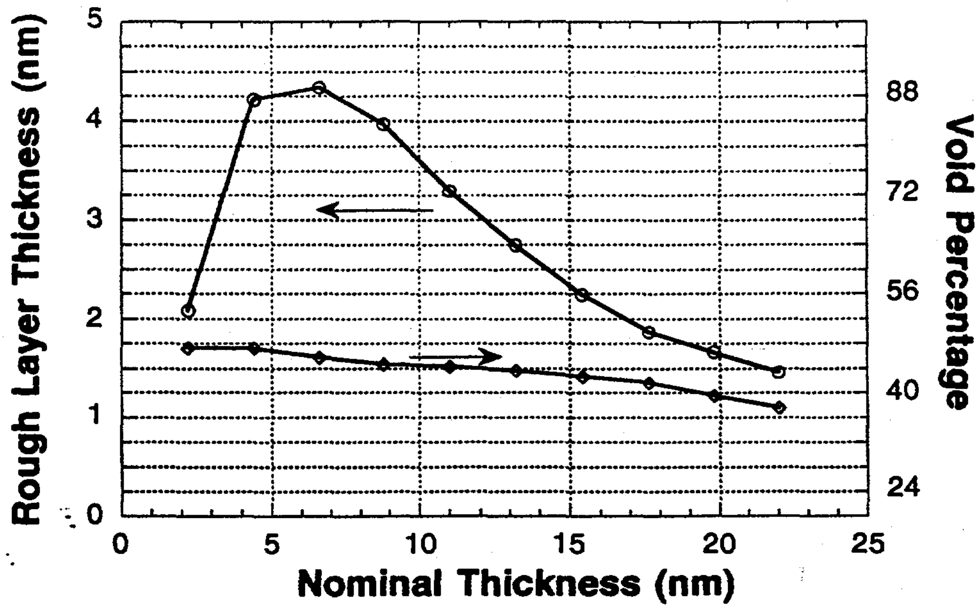




Liu, figure 6



Liu, figure 7