Reactive co-sputtering of hematite doped silica ($\text{Fe}_2\text{O}_3\text{-SiO}_2$) thin films

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1. Introduction

Iron oxide thin films have generated significant interest for applications in optics and energy generation due to their unique optical and electronic properties. For instance, FeO and Fe₂O₃, have absorption features in the ultraviolet and near-infrared, at approximately 380 and 1050 nm, respectively [1-4]. As a result of their optical characteristics, Fe-O compounds are a common ingredient in silica based heat-absorbing glasses, where both the UV and IR transmission can be tailored simultaneously by adjusting the ratio of Fe³⁺ and Fe²⁺ species [3]. As such, the UV and IR absorbing properties of Fe-doped glasses find uses in energy efficient architectural windows [2, 5] and in ophthalmic glasses for protection against UV-induced damage [2, 6-8]. However, the applications of iron oxides are not limited to usage in bulk glasses. For instance, the absorption features of FeO and Fe₂O₃, make iron oxides useful for spectrally selective coatings for both energy generation [7, 9, 10], and electrochromic materials for “smart window” applications [11, 12]. Due to its high refractive index, $n_{589}=3.10$ [13], Fe₂O₃ could also be a useful high index material in optical interference filters due its large index excursion relative to SiO₂, $n_{589}=1.46$ [14]. Additional applications for iron oxide thin films include gas sensing [15-17], catalysis [18, 19], and photoelectrode junctions within devices used for hydrogen generation [20-24].

Based on the aforementioned applications, namely smart windows, heat absorbing glasses, and interference coatings, it is evident that a relatively high degree of optical transparency is required. However, since Fe₂O₃ has a band gap that typically falls between 1.5 and 2.0 [25-27], it is common to utilize Fe-O compounds as a dopant within a transparent matrix, typically SiO₂ [3, 5, 18, 28, 29]. While mixtures of silica doped with iron are frequently found in bulk glasses [3, 4, 8], several methods have been explored for doping iron with silica through

sol-gel processes [18, 28, 30], magnetron sputtering [5, 31-36], and chemical vapor deposition [12]. While all of the fabrication methods mentioned are capable of depositing quality films under the proper conditions, the high deposition rates, industrial scalability, and composition control afforded by reactive magnetron co-sputtering [37] make it a prime candidate for deposition of thin films within the Fe-Si-O material system. Note that while the majority of the magnetron sputtering related studies focus on maximizing the magnetic properties of metallic Fe within a silica matrix [31-36], these studies provide useful insights into processing methods for the Fe-Si-O material system. Given the large emphasis on magnetic properties within the literature, very few systematic studies relating deposition conditions, composition, chemistry, and optical properties, are available. One such study that explores the optical properties of sputtered Fe-Si-O films include work by Gil-Rostra et al. analyzing the optical and chemical properties of films with varying Fe_2O_3 content, as determined by the number of iron strips placed on the surface of a Si sputter target [5]. While useful for incrementally varying the ratio of iron to silicon, the strip method lacks both the scalability and stability of the co-sputtering approach.

This work presents a description of a scalable reactive magnetron co-sputtering process used to systematically control the amount of Fe_2O_3 within a SiO_2 matrix by establishing a process-property relationship correlating the power applied to the Fe sputter source to the resulting Fe content in mixed Fe_2O_3 - SiO_2 films. This study also aims to develop a process-property correlation capable of explaining the effects of Fe^{3+} content, within an SiO_2 matrix, on the resulting optical properties of the films, namely the spectral refractive index, $n(\lambda)$, extinction coefficient, $k(\lambda)$, and optical gap, E_g . The process-property correlation established within this work is expected to act as a template for the selection of conditions required to tailor the Fe content in order to achieve the desired optical performance. Analysis of composition and optical

properties is performed using x-ray photoelectron spectroscopy (XPS) and spectroscopic ellipsometry (SE), respectively. Films deposited using the methods outlined within this work demonstrate E_g values ranging from highly transparent at above 3.5 eV, down to 1.52 eV, within the range for devices requiring efficient absorption of solar energy [2, 38, 39].

2. Experimental

Fe doped SiO_2 thin films were grown within a high vacuum chamber equipped with two 50 mm magnetron sputter sources, as previously described in Refs. [40, 41]. Prior to deposition, the vacuum chamber was evacuated, using turbomolecular pumping, to a pressure of 5.0 E^{-7} Torr, or better. Upon achieving an adequate base pressure, 1x1 cm Si (100) substrates (University Wafer LLC) were introduced through a load-lock chamber. The reactive deposition atmosphere was achieved by flowing 6 sccm of oxygen and 25 sccm of argon through separate mass flow controllers with outlets located near the substrate and magnetron sources, respectively. The working pressure of argon was held at 2 mTorr, corresponding to a constant pumping speed of 128 l/s, prior to the introduction of oxygen. A constant pumping speed was achieved by locking the position of the gate valve between the turbomolecular pump and the chamber. The total working pressure (P_{TOT}) and the corresponding oxygen partial pressure (P_{O_2}) were monitored using a capacitance manometer. Quantification of the oxygen partial pressure relies on the assumption that only negligible amounts of Ar are lost due to ion implantation [42]. To facilitate deposition of the Fe-Si-O films, separate Si (K.J. Lesker, 99.999%) and Fe (Alfa Aesar, 99.95%) targets were affixed to confocally arranged magnetron sources placed 13 cm away from the substrate. Note that the Fe targets used within this experiment were made in-house by affixing 25 μm thick Fe foil to a 50 mm diameter copper backing plate with molten indium per Ref. [43]. Plasma was generated using an Advanced Energy Pinnacle Plus pulsed-DC power

supply for the SiO₂ deposition and an Advanced Energy MDX DC power supply for Fe₂O₃. Pulsed DC magnetron sputtering (PDCMS) was used to deposit SiO₂ due to its ability to generate bi-polar voltage pulses, allowing for the mitigation of arc events commonly observed when depositing highly dielectric materials [44, 45]. The Fe source power (W_{Fe}) was adjusted from 20 to 80 W in steps of 10 W in an effort to vary the Fe₂O₃ content relative to SiO₂. Deposition conditions as a function of W_{Fe} , including P_{TOT} , current (I) and voltage (V) levels for both Fe and Si sources are listed in Table 1. No heating, aside from thermal contributions of the plasma, was used during the deposition of these films. As such, all films were found to be amorphous via grazing incidence x-ray diffraction analysis (data not shown).

X-ray photoelectron spectroscopy (XPS) analysis was employed to measure the composition and chemistry of the compounds present in the deposited films. XPS survey and high energy resolution scans were obtained using a Physical Electronics 5700 equipped with a monochromatic Al K α (1486.6 eV) x-ray source. Compositional analysis was performed using survey scans at an analyzer pass energy of 187.85 eV in a binding energy range spanning 0-1400 eV, while an analyzer pass energy of 29.35 eV was used for high energy resolution measurements to examine the chemical valence states of the deposited species. In order to correct for charging, all spectra were calibrated with respect to the adventitious carbon 1s transition at a binding energy (BE) of 284.6 eV. High energy resolution scans were fit using asymmetric line shapes following Shirley background subtraction, while shake-up peaks were fit using 70% Gaussian-30% Lorentzian line shapes. XPS data processing was performed using the CasaXPS 2.3.16 software package [46]. Note that doublet peak spacing, peak area ratios, and peak full-width half-maxima were all constrained in an effort to increase fit accuracy.

The optical properties of the Fe-Si-O films were measured using a J.A. Woollam α -SE spectroscopic ellipsometer (SE) and fit using the CompleteEase software package. The α -SE data was collected over a wavelength range of 381-900 nm (1.37-3.25 eV). Raw ellipsometry data was gathered by monitoring the changes in both the magnitude (Ψ) and phase difference (Δ) of polarized light after interaction with the sample surface at angles of incidence of 70° and 75°. Note that the spectral refractive index, $n(\lambda)$, the extinction coefficient, $k(\lambda)$, and the thickness of the films were calculated by fitting raw SE data with a Kramers-Kronig consistent optical model, described in section 3, and the resulting mean squared error (MSE) was minimized through iterative adjustment of the fitting parameters using the Levenberg-Marquardt method, improving the fit quality. Fits with an MSE greater than 12 were rejected.

3. Results and Discussion

3.1 Composition and chemistry measurement

Quantitative analysis of the composition of the deposited Fe-Si-O films (Figure 1) indicates that the only detectable elements on the film surface are iron, silicon, oxygen and adventitious carbon. The presence of adventitious carbon, at concentrations of approximately 4-10 at%, is the result of atmospheric exposure occurring during transportation from the deposition chamber to the analysis chamber. The amount of adventitious carbon increases nearly 6% as W_{Fe} is increased from 20 to 80 W, a potential result of favorable bonding conditions with Fe oxide species on the film surface. In addition to increases in carbon, increases in W_{Fe} directly correlate to increases in Fe content and, subsequently, decreases in Si concentration within the films. Film surface compositions measured from XPS survey scans are listed in Table 2. Comparison of the composition measurements in Table 2 to the deposition currents (Table 1) indicates that, as W_{Fe} increases from 20-80, the resulting current (I_{Fe}) increases from 0.050 to 0.181 A, resulting in an

increase in Fe composition from <1 to 4 at.%. Correspondingly, the current applied to the silicon source (I_{Si}) decreases from 0.42 to 0.39 A, related to a drop in concentration from 28 to 22 at.%. While the increase in I_{Fe} is the direct result of increasing W_{Fe} , the corresponding decreases in I_{Si} are the result of decreases in the ion-induced secondary electron emission coefficient (ISEE) corresponding to increased oxygen gettering events related to chemisorption attributed to the increasing iron deposition flux [47-49]. Note that the oxidized silicon has been shown to have a higher ISEE than metallic silicon, as discussed in Ref. [47], resulting in lower current levels as the amount of available oxygen decreases. The evidence of oxygen gettering, as a function of increasing W_{Fe} , is corroborated by the decrease in P_{O_2} , from 0.4 to 0.3 mTorr, shown in Table 1. The observed effects of increases in W_{Fe} on the discharge behavior of the Si source provide evidence of complex interactions between the Si and Fe targets during co-deposition.

In addition to composition measurements, the chemistry of the resulting Si-O and Fe-O compounds was explored using XPS. XPS high energy resolutions scans were acquired in order to determine the effects of changes in W_{Fe} on the resulting oxides formed by the co-sputtering process. High energy resolution scans of the Si 2p, Fe 2p, and O 1s transitions, as well as associated components obtained via curve-fitting, are shown in Figure 2-4, respectively. Analysis of the Si 2p core level spectra (Figure 2) indicates very little sensitivity to changes in W_{Fe} , aside from a gradual binding energy (BE) shift from 102.8 to 102.1 eV, a potential result of nearest neighbor interactions with increasing amounts of Fe, as W_{Fe} increases. Interaction with Fe results in a BE that is slightly lower than previously reported values for SiO_2 near 103.2 eV [50, 51]. Analysis of the Fe 2p doublet (Figure 3) also indicates minimal sensitivity to increases in W_{Fe} , aside from increased signal-to-noise as a result of the increasing Fe composition. The observed increases in signal quality, for $W_{Fe} > 40$ W, attribute to the detection of the shake-up peaks located

near 719.3 and 733.0 eV. The separations of the satellite peaks, and their associated Fe 2p peaks, are approximately 8.0 eV, similar to spacings reported by Aronniemi et al. for Fe₂O₃ [52]. Additionally, BE values for the Fe 2p_{3/2} peaks, approximately 711.5 eV, fall within the range of previously reported values for Fe₂O₃ ranging from 710.6-711.6 eV [52, 53]. Further examination of the O 1s core level transition (Figure 4) indicates the presence of two components centered at approximately 532.3 and 530.4 eV, consistent with reported values for SiO₂ (532.6-532.3 eV) [54] [51] and Fe₂O₃ (529.6-530.2 eV) [55, 56]. Additionally, the intensity of the low-BE component associated with Fe₂O₃ appears to increase alongside W_{Fe}. To further examine any relationship between the signal intensities attributed to the O 1s components, and those of the Si 2p and Fe 2p_{3/2} transitions, the ratio of each of their raw areas was calculated. Table 3 shows the results of the ratios of the raw survey scan areas of the Si 2p survey region and the high BE O 1s component, as well as the Fe 2p_{3/2} region and the low BE O 1s component. Based on the ratios shown in Table 3, it is evident that the O 1s components attributed to both Fe₂O₃ and SiO₂ are directly proportional to their respective raw survey scan areas. The average ratio of Fe 2p peak area to that of the low BE O 1s component is 0.51, with a standard deviation of 0.09. For Si-attributed peaks, the average ratio is 0.20, with a standard deviation of 0.01. Based on the consistency of these ratios, it is possible to calculate a new set of sensitivity factors for the quantification of the relative amounts of Fe and Si using only their O 1s component areas. In order to calculate the sensitivity factors attributed to the O 1s component areas, the respective sensitivity factors for Fe 2p_{3/2} and Si 2p, 1.78 and 0.31, were divided by the average ratios of 0.51 and 0.20, respectively. Sensitivity factor calculations result in factors of 3.51 and 1.47 for the Fe and Si O 1s components. Fe and Si concentrations calculated using sensitivity factors for the O 1s components are plotted alongside compositions calculated using the Si 2p and Fe 2p_{3/2}

transitions in Figure 5. Determination of sensitivity factors related to specific O 1s components not only validates the results of compositions determined by survey scan measurements, but provides an accurate way to directly measure $\text{Fe}_2\text{O}_3\text{-SiO}_2$ film composition based on the O 1s transition.

3.2 Optical characterization

Raw polarization data, measured using SE, was fit using a Tauc-Lorentz oscillator to model the spectral optical constants, $n(\lambda)$ and $k(\lambda)$, of the Fe-Si-O films. In addition to optical constants, the surface roughness, film thickness, and E_g were also measured. The model used to fit the raw data is based on a layered structure consisting of four discrete layers, listed from bottom to top: silicon substrate, a 2 nm Si native oxide, a Tauc-Lorentz Fe-Si-O layer of variable thickness, and a 50% void fraction Bruggeman effective medium layer to approximate surface roughness. Note that the Tauc-Lorentz oscillator, described in detail elsewhere [57], is commonly used for characterization of amorphous, semiconducting materials due to its ability to accurately parameterize the optical band gap, E_g . The agreement between the raw polarization data, ψ and Δ , and the model calculations, is shown in Figure 6. Note that the most predominant changes in the appearance of ψ and Δ are the result of interference induced oscillations as the optical thickness of the films increases alongside increases in W_{Fe} . The quality of the aforementioned model is demonstrated by MSE values ranging from 3.99 to 11.33, as shown in Table 4. In addition to MSE values, Table 4 also includes thickness, deposition rate, roughness, E_g values, and associated error bounds. Note that all of the aforementioned parameters demonstrate a high degree of sensitivity to changes in W_{Fe} . Changes in thickness, and subsequent deposition rates, can be mainly attributed to the increased Fe deposition flux attributed increases in W_{Fe} .

Roughness values also demonstrate significant sensitivity to increases in W_{Fe} , a potential result of the decrease in P_{O_2} related to chemisorption attributed to the augmented Fe deposition flux. The observed decreases in P_{O_2} , from 0.4 to 0.3 mTorr, likely facilitate nucleation of larger grains by delaying the formation of the surface coating layer of oxygen commonly associated with grain refinement [58, 59].

Spectral values of n and k , calculated using the aforementioned optical model, are shown in Figure 7 and Figure 8, respectively. Analysis of the response of n_{589} , for $20 \leq W_{\text{Fe}} \leq 80$ W indicates a gradual increase from 1.48 to 1.66. The observed increases in $n(\lambda)$ are associated with the larger fraction of Fe_2O_3 , $n_{589}=3.10$ [13], relative to SiO_2 , $n_{589}=1.46$ [14], as it increases from 0.01 to 0.15. Increases in $n(\lambda)$ can be roughly approximated using a Bruggeman effective medium approximation (EMA), which assumes the phase separation of Si-O-Si and Fe-O-Fe bond configurations, as shown in Figure 7 (inset). While the general trend established by the EMA agrees with the measured results, the predicted index is slightly lower than values obtained via ellipsometry. The slight mismatch between the EMA and measured values is a potential result of nearest-neighbor polarization effects, related to the formation of Fe-O-Si bonding structures [5], between Fe_2O_3 and SiO_2 . As for calculations of $n(\lambda)$, modeling of $k(\lambda)$ also indicated systematic changes as a result of increasing W_{Fe} from 20 to 80 W. As depicted in Figure 8, the only absorption present in the measured spectral range can be attributed to the optical band gap, E_g . As such, no evidence of the tail of the dominant near-IR absorption feature attributed to FeO ($\lambda=1055$ nm) is apparent. The lack of absorption features characteristic of FeO corroborates the findings of the XPS analysis, confirming that iron is only present in the Fe^{3+} valence state for $20 \leq W_{\text{Fe}} \leq 80$ W. As W_{Fe} was increased from 20 to 30 W, E_g values remain above 3.5 eV, outside of the detection range of the α -SE ellipsometer. As such, E_g values for

these films cannot be calculated, resulting in the high error bounds shown in Table 4. However, note that the inability to calculate E_g does not adversely affect the MSE. Upon increasing W_{Fe} to 40 W, the absorption attributed to E_g falls within the range of the ellipsometer detector, $E_g=2.99\pm0.03$ eV, as shown in both Table 4 and Figure 8. The E_g of the Fe_2O_3 continues to gradually decrease from 2.99 eV at $W_{Fe}=40$ W to 1.52 eV at $W_{Fe}=80$ W, corresponding to respective k values of 0.00 and 0.08 at 400 nm. The observed E_g of 1.52 eV at 80 W is consistent with values reported by Akl et al. parameterizing the indirect band transition of amorphous Fe_2O_3 [39]. Furthermore, attaining an E_g similar to that of amorphous Fe_2O_3 is further evidence of the presence of Fe_2O_3 clusters or agglomerates within the SiO_2 matrix, as previously observed by Gil-Rostra et al. for mixed transition metal-silicon oxides [5]. The decrease in E_g , as a function of W_{Fe} , is directly correlated to the increase in Fe_2O_3 relative to SiO_2 . As shown in Figure 9, the coloration of the films changes dramatically as W_{Fe} increases from 20 to 80 W. The observed change in coloration, as a function of increasing W_{Fe} , is a direct result of interference effects, where the reflectivity of the films is influenced by the product of the refractive index and the film thickness, also known as the optical thickness. As W_{Fe} increases, the optical thickness also increases due to the augmentation of both $n(\lambda)$ and the deposition rate. The observed increases in optical thickness causes the observed red-shifting of film reflectance, giving rise to the changes in coloration in Figure 9. Based on the relatively small magnitude of $k_{589}=0.05$, at $W_{Fe}=80$ W, it is unlikely that absorption plays a significant role in the appearance of the films.

Changes in W_{Fe} give rise to significant changes in the composition and optical properties of the films. As previously noted, increases in Fe content are directly correlated to increases in n and k values, and decreases in E_g . The overlay plot, shown in Figure 10, helps to depict the relationship between processing, Fe content, and E_g . Specifically, Figure 10 shows the effects of

changes in W_{Fe} on E_g , Fe content, and the applied current to the Fe source (I_{Fe}). As W_{Fe} is increased from 20 to 80 W, I_{Fe} experiences an approximately linear increase from 0.050 to 0.181 A. The augmentation of I_{Fe} , as a function of W_{Fe} , results in an approximately exponential increase in Fe content. Given the linear increase of I_{Fe} , it is likely that the observed exponential rise in Fe content, relative to Si, is the result of the depression of the deposition rate of SiO_2 . The behavior of E_g , with respect to W_{Fe} , exceeds 3.5 eV at W_{Fe} values of 20 and 30 W, then demonstrates a non-linear decrease from 2.99 to 1.52 as Fe content increases for increasing W_{Fe} from 40 to 80 W. Therefore, a simple rule-of-mixtures model cannot account for the changes in the band gap for W_{Fe} values greater than or equal to 40 W. A potential mechanism describing the behavior of E_g , with respect to Fe content, is based upon the transition from a network comprised largely of random solid solution of Fe^{3+} cations within and SiO_2 matrix, corresponding to Fe-O-Si bonding structures, to the formation of phase separated Fe-O-Fe bonds. Once the concentration of Fe^{3+} cations exceeds the solid solubility limit, in this case, above a Fe_2O_3 fraction of 0.02, within the SiO_2 matrix, Fe-O-Fe bonds begin to form. Note that further work would be required to determine the morphology of potential structures formed by Fe-O-Fe bonding.

4. Conclusion

The reactive co-sputtering approach used within this work demonstrates the ability to systematically control the amount Fe_2O_3 relative to SiO_2 through variation of W_{Fe} . By adjusting W_{Fe} from 20 to 80 W, the Fe_2O_3 fraction within the films was shown to range between 0.01 and 0.15, relative to SiO_2 , resulting in significant changes in the refractive index, extinction coefficient and optical band gap. With respect to the optical constants, increases in Fe_2O_3 content were associated with a rise in refractive index values from $n_{589}=1.48$ to $n_{589}=1.72$. Additionally,

the extinction values increased, alongside W_{Fe} , from k_{589} remained below 0.01, as E_g decreased from above 3.5 eV to 1.52 eV. Finally, a process-property correlation was developed to determine the relationship between deposition power, applied current, and E_g , providing an experimental template for users seeking to tune the optical properties of mixed Fe_2O_3 - SiO_2 thin films. The ability to tailor the Fe_2O_3 fraction using the methods described within this work could allow for the deposition of Fe_2O_3 - SiO_2 films with a wide variety of optical properties useful for applications ranging from UV blocking ophthalmics and interference filters, to spectrally selective coatings used for solar energy generation.

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5. References

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Figure Captions

Figure 1. XPS survey spectra for Fe power levels of 80 and 20 W. The spectra are offset for clarity.

Figure 2. XPS high energy resolution scans of Si 2p core level transition for levels of W_{Fe} from 20 to 80 W.

Figure 3. XPS high energy resolution scans of Fe 2p core level transition for levels of W_{Fe} from 20 to 80 W. Note that there is not sufficient signal-to-noise to resolve the Fe satellite peaks for W_{Fe} values less than 50 W.

Figure 4. XPS high energy resolution scan of O1s core level transition for levels of W_{Fe} from 20 to 80 W. Note the two distinct components correlating to oxygen in SiO_2 and Fe_2O_3 .

Figure 5. Scatter plot of compositions derived from the Si 2p and Fe 2p_{3/2} transitions, as well as experimentally derived compositions based on O 1s components corresponding to Si and Fe compounds.

Figure 6. Selected raw ellipsometry data measured at 70° and 75°, for W_{Fe} =20 (a), 50 (b), and 80 W (c), fit using a Tauc-Lorentz oscillator model. Note the excellent agreement between the measured data (solid) and model (dashed). The changes in ψ and Δ , with W_{Fe} , are largely the result of interference effects due to the interaction of light reflected from the top and bottom surfaces of the films.

Figure 7. Plot of the spectral refractive index for W_{Fe} values ranging from 20 to 80 W.

Figure 8. Plot of the spectral refractive index for W_{Fe} values ranging from 20 to 80 W.

Figure 9. Photograph of Fe_2O_3 - SiO_2 films deposited on silicon. Samples are arrayed by increasing W_{Fe} values from 20 to 80 W, left to right.

Figure 10. Overlay plot demonstrating the relationship between the band gap, iron content, and deposition current as a function of W_{Fe} . Fe compositions in this plot are relative to Si content, neglecting adventitious carbon and oxygen.

Table 1. Response of oxygen partial pressure, voltage, and current, as a function of increasing Fe source power (W_{Fe})

W_{Fe} (W) ^a	P_{O2} (mTorr)	V_{Fe} (V)	I_{Fe} (A)	V_{Si} (V) ^b	I_{Si} (A)
20	0.4	382	0.050	478	0.42
30	0.4	386	0.076	484	0.41
40	0.4	416	0.095	476	0.42
50	0.4	428	0.116	497	0.40
60	0.3	452	0.132	501	0.40
70	0.3	449	0.156	507	0.39
80	0.3	443	0.181	518	0.39

^aSetpoint power, ^bSi source operated at 200W, 75 kHz, 3us rev time

Table 2

Table 2. Compositions obtained from XPS survey scans.

Atomic Concentration (at.%)					Fe ₂ O ₃ fraction
W _{Fe} (W)	C 1s	O 1s	Si 2p	Fe 2p _{3/2}	Fe ₂ O ₃ /(Fe ₂ O ₃ +SiO ₂)
20	4	68	28	<1	0.01
30	5	67	28	1	0.02
40	6	66	27	1	0.03
50	8	66	25	1	0.05
60	7	66	26	2	0.06
70	8	66	23	3	0.10
80	10	64	22	4	0.15

Table 3

Table 3. Survey scan areas for Si 2p and Fe 2p_{3/2} regions compared with areas of high and low binding energy components of the O 1s transition, corresponding to SiO₂ and Fe₂O₃, respectively. Note that the O 1s component areas were measured using high energy resolution scans.

W_{Fe} (W)	Survey scan areas*		O 1s component areas*		Area Ratios	
	Si 2p	Fe 2p_{3/2}	SiO₂ (~532.1 eV)	Fe₂O₃ (~530.5 eV)	Si 2p/SiO₂	Fe 2p_{3/2}/ Fe₂O₃
20	1384	93	7171	183	0.19	0.51
30	1448	138	7107	331	0.20	0.42
40	1366	230	6898	347	0.20	0.66
50	1167	342	5710	782	0.20	0.44
60	1117	422	5389	919	0.21	0.46
70	974	617	4422	1382	0.22	0.45
80	944	867	4034	1421	0.23	0.61

*Calculated area=(Area/(T*MFP)), area units: CPS*eV, where T is the analyzer transmission, MFP is the electron mean free path, and CPS is counts per second.

Table 4

Table 4. Selected parameters, obtained via ellipsometry measurements, as a function of Fe source power (W_{Fe}). Note that the band edge values in italics exceed the maximum range of the ellipsometer (3.25 eV) and, thus, are unable to be fit accurately.

W_{Fe} (W)	MSE	Roughness (nm)		Thickness (nm)		Deposition Rate (nm/min)	Band Edge (eV)	
20	11.36	0.0	± 1.9	182.1	± 0.2	18.2	<i>3.51</i>	<i>± 171</i>
30	11.33	0.0	± 2.0	177.2	± 0.2	17.7	<i>3.50</i>	<i>± 849</i>
40	6.29	0.0	± 1.0	151.8	± 0.1	15.1	2.99	± 0.03
50	3.46	0.2	± 0.4	209.4	± 0.1	20.9	2.71	± 0.01
60	4.74	2.5	± 0.3	211.9	± 0.2	21.1	2.66	± 0.01
70	7.85	7.4	± 0.6	235.5	± 0.5	23.5	2.48	± 0.01
80	3.99	7.4	± 0.2	251.8	± 0.2	25.1	1.52	± 0.03

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10