Process Improvement and Cost Reduction Utilizing a Fully Automated CD SEM for Thin Film Head Pole 2 Resist Measurements

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ABSTRACT

Thin Film Head (TFH) manufacturers are constantly striving to improve process control, eliminate scrap material and reduce the total cost of manufacturing their devices. Successful measurement and control of the Pole 2 Resist structure is a critical component of the TFH process which directly impacts disk drive performance, reliability and final product cost. Until recently, white light optical metrology systems have been the only option for measuring the Pole 2 structures. However, recent advances in TFH process technology have resulted in aspect ratios of greater than 10:1 which has limited the ability of the white light optical metrology systems. IVS has developed a unique metrology solution to image and measure these high aspect ratio structures utilizing the IVS-200 CD SEM. This technology provides state of the art measurement performance for repeatability and stability which in turn has provided manufacturers with the ability to monitor the Pole 2 process and reap both technical and financial benefits.

KEYWORDS

Thin Film Heads; Pole 2; Top Pole; Scanning Electron Microscopy (SEM); Metrology

1. INTRODUCTION

In the manufacture of disk and tape drives, one of the most important components is the Thin Film Head (TFH) structure. The track width of the magnetic poles on the head define how tightly spaced the data can be stored onto the magnetic material. In the manufacture of both Inductive and Magneto-Resistive (MR) heads, the top pole (commonly referred to as Pole 2) has historically been the most difficult and critical photolithography process step in TFH manufacturing.

The manufacturing challenge is created by the topography and geometry of the underlying coil structure on which the Pole 2 structure is placed. The process of creating the second magnetic pole structure requires a very thick resist of up to 30 microns to be coated onto the substrate resulting in aspect ratios of up to 10:1. The Pole 2 resist structure is a trench into which a layer of nickel iron plating is deposited. This lift-off type process is utilized to allow the nickel iron (up to 5 microns thick) to flow over the large topographies of the underlying coil. After an ion milling of the pole and ensuing insulating layer deposition, the devices are cut into row bars and lapped down to a point approximately 2 microns below what is referred to as zero throat (where the pole meets the coil). It is therefore critical to control the width of the Pole 2 structure just below zero throat. This is referred to as the track width and is the leading performance characteristic of a TFH device.

The photolithography process engineer is faced with two technical challenges in order to produce and control the Pole 2 structure. The first is printing the feature using stepper optics that have been specifically designed to generate a large depth of focus. The second is the measurement of the resist feature which has become a focal point for major yield improvements and scrap reductions in the TFH process.

1.1 Thin Film Head Substrate Diversity

The first challenge in manufacturing metrology systems for TFH structures is the diversity of processes and substrate materials utilized by the industry. The industry has yet to follow the lead of the semiconductor industry where standards exist on the size, shape and thickness of the substrates. The TFH industry contains a multitude of substrates that must be accommodated by the metrology systems. One area that has seen standardization is the thickness of the substrate which started at 4.0mm. The industry quickly moved to the 2.8mm (70%) generation and has more recently been working with 2.0mm (50%) and 1.2mm (30%) thick substrates. However, a lack of standardization in the size and shape has resulted in a plethora of substrate combinations including 3" - 6" round and 4" to 6" square as very common materials.

1.2 Optical Metrology

Historically, the Pole 2 feature has been measured by optical metrology systems. This methodology has worked for a number of years, but the increase in the thickness of the resist and the decrease in feature size have caused the aspect ratios to approach ten to one. Optical measurements of small features with high aspect ratios can only be achieved with high numerical aperture optics resulting in narrow depth of fields. High resolution is achieved only by a cone of light that has a large angle of incidence.

Ernst Abbe specified the limit of resolution of a diffraction limited microscope. He said that a detail with a particular spacing in the specimen is resolved when the numerical aperture of the objective lens is large enough to capture the first order diffraction pattern produced by the detail at the wavelength employed. Abbe, along with Sparrow and Lord Raleigh, defined resolution as it applies to two dimensional features[1].

Depth of field has an inverse relationship to numerical aperture. As numerical aperture increases, the depth of field of the system decreases. Depth of field is defined as the distance between the closest and farthest objects that are in focus within a given image. The depth of field of a high resolution optical microscope is typically a small fraction of a micron. Semi-transparent structures such as resist trenches with high aspect ratios make the resolution equation much more complex.

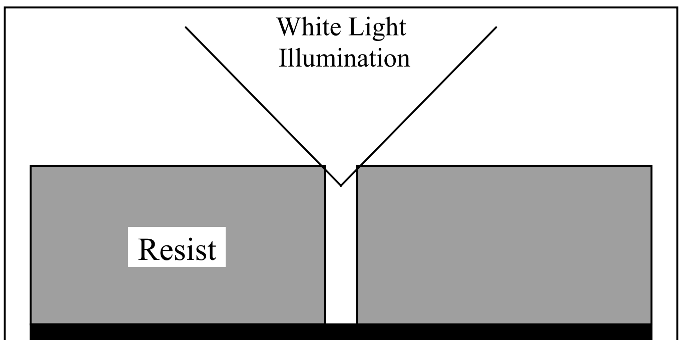

Figure 1. A representation of high N/A white light illumination of a 5µ trench in 30µ of resist.

With aspect ratios of greater than two it becomes very difficult for an optical microscope to resolve the bottom of trenches in resist. With aspect ratios as high as 10:1 for TFH Pole 2 features, the optical microscope has far surpassed its imaging capabilities for this process technology. The required numerical aperture for high resolution optical microscopy runs between 0.60 and 0.95 in air. This translates to a half angle of the cone of illumination of between 35° and 70°. This cone of illumination is demonstrated in Figure 1 provided to the left of this text.

The requirements of high resolution and large depth of field in an optical microscope are not compatible as defined by the physics of optics. Figure 1 shows how this affect translates to a 5µ trench in 30µ of resist. Note that the high numerical aperture and small depth of field of the optical microscope make it impossible for the system to adequately image the bottom of the trench. The varying refractive index of the resist also causes refractive interference at all levels of the trench that make accurate measurement of the feature improbable.

A popular variation is the interference microscope which uses coherence information to formulate an image. This approach forms a pseudo image from many images taken at different points in the Z plane. However, this is a white light system that has most of the same limitations of standard broad band optics. The depth of field is still very small and a high N/A lens is utilized to achieve the resolution required. This means that the information required to accurately measure the edge is not available in high aspect ratio features. The interference approach also adds a high level of complexity to the optics and the system which results in a system that is very difficult to maintain.

1.3 The Automated Scanning Electron Microscope

The ability to accurately image the bottom of the Pole 2 resist structure combined with a manufacturing requirement for full hands-off automation are key components for the TFH production process. In the search of a technique to successfully image and measure the bottom of a Pole 2 resist feature, a new breed of automated Critical Dimension Scanning Electron Microscope (CD SEM) Metrology System stands out as the most capable technology. SEMs have been used for a number of years in the failure analysis labs of many semiconductor houses and TFH manufacturers. They have been able to provide a wealth of information from the images obtained. The SEM has been used to analyze cross sections of sacrificed TFH product, but the one thing that the SEM has not been able to provide are accurate and repeatable measurements on the production floor. The reasons for this limitation are the measurements have been too operator dependent and the equipment has not been manufactured with long term stability in mind. The automated CD SEM is designed with full hands off automation and long term measurement stability in mind. The combination of these two features has minimized the barrier of entry for the CD SEM technology to be implemented in the TFH Pole 2 process flow.

For example, system adjustments are no longer required on a site by site basis and are not available to the operator. The stability of the system parameters that were once counted in hours are now counted in shifts, days, weeks or even months. More advanced CD SEMs have replaced all of the analog control circuitry with full digital designs whereby all inputs are digitally encoded and controlled by firmware and software. This assures that the system can run for long periods of time with minimal supervision. Additionally, full hands off automation for running production lots requires robust pattern recognition and software technology to allow the CD SEM to move to the correct sites to be measured. This is not a trivial matter since pattern recognition of SEM images is not straight forward. Advanced image processing is required to extract the relevant signal from the SEM image to perform pattern recognition. The automation of the SEM and the system stability are important factors in its use on the TFH production floor.

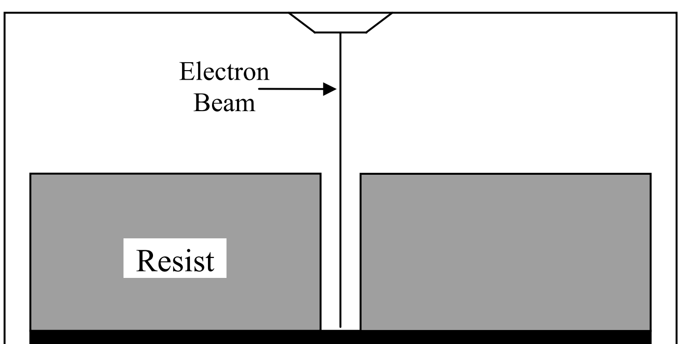

Figure 2. A representation of a SEM electron beam in relation to a 5µ trench in 30µ of resist.

However, the most important factor is its ability to measure features that can not be measured by other means. This brings us to the comparison of the SEM to the optical microscope in its ability to image and measure the Pole 2 resist structures. The equivalent to N/A in a scanning electron microscope is called angle aperture. It is defined at the half angle of the cone of electrons coming from the final lens or final lens aperture to the specimen[2]. The angle aperture of an electron beam can be as small as hundredths of a degree depending on the design of the final lens system resulting in very large depths of field. The depth of field of the SEM can be as large as 50µ at 10,000x which allows the system to image the entire Pole 2 structure in a single focal plane. This also allows the beam to get to the bottom of the feature and return to the detector in the form of backscatter and secondary electrons to form an accurate image undisturbed by issues of diffraction, refraction and depth of field.

Once the system has been provided with an accurate and repeatable image, it is equally important to analyze the image correctly. The measurement algorithms are a critical component to the determination of the Pole 2 width. The semiconductor measurement algorithms have not provided the level of measurement performance and correlation capability required for the TFH technology. This is probably related to the differences in the resist processing technology, aspect ratios and side wall profiles between a standard semiconductor feature and the TFH Pole 2 structure. Therefore, new measurement algorithms have been developed specifically to deal with the large aspect ratios and other unique challenges of the Pole 2 photo process in the TFH industry.

TFH features have a very different set of requirements for measurement than the relatively two dimensional features of the semiconductor industry. Because of the physical profile of the resist line and the subsequent plating process, the definition of the bottom of the resist trench is critical. Algorithms commonly used for measurement of semiconductor features therefore become unusable. Also, resist pinching and scumming are more common problems as the resist and stepper technologies are stretched to their limits. A phenomenon known as necking is also something that needs to be monitored. The trench CD changes as the feature approaches the critical juncture known as zero throat.

The above requirements mean that much more analysis must take place on a single feature than before which can severely affect the system throughput if the system is not designed to handle the large amounts of information and make multiple measurements without a significant impact in the time spent at any single site. All of these considerations lead us to examining the methods that are required to measure these unique features that have such a profound affect on the performance of a TFH device.

2. METHODS

A set of hardware configurations and suite of measurement algorithms were developed on the IVS-200™ Submicron CD SEM Metrology System for the measurement of TFH Pole 2 structures. This has provided the TFH manufacturer with an option of utilizing a fully automated CD SEM for the measurement of the Pole 2 structures instead of the technology limited optical metrology systems of the past.

2.1 Hardware Requirements

Probably the most important component of any metrology system is the hardware needed to provide the accurate and repeatable images that are required for measurement. The old saying of 'trash in, trash out' tells us that if one does not begin with accurate repeatable images, one can not hope to get accurate and repeatable measurements.

A combination of long focal length and small e-beam diameter at the final lens give us a very small aperture angle[2] and therefore a very large depth of field. This is a requirement that cannot be ignored in an industry where resist thickness can easily reach 30µ. A depth of field that is greater than 30µ at 10,000x allows the system to focus both on the top and bottom of the resist feature during the same image acquisition. Out of focus information will be blurred on the SEM similar to the white light optical microscope. This can adversely affect the accuracy of the image and therefore the measurement. Systems with immersion lens technology, for instance, are great for optimal resolution on two dimensional structures but the fact that focal length has been reduced effectively to zero will cause the aperture angle[2] to increase and therefore affect the depth of field.

Another parameter of the electron source that must be closely monitored is gun voltage. Before the advent of low voltage SEMs, in-line process monitoring was impossible. This was due to the high voltage causing charge effects in the materials being imaged in the SEM. With a high voltage system, all samples are gold coated prior to examination and measurement in the SEM. The advent of low voltage systems, that operate from just over 1 KeV to less than half that value, have made in-line process monitoring possible. The beam can charge the resist and even cause permanent damage to underlying layers. This is especially critical in the TFH industry where the magnetic properties of the device can be adversely affected by an electrical charge. Charging caused by high gun voltages can also lead to poor measurements. The image can be adversely affected to the point that measurements can vary widely from their actual values. The higher the gun voltage, the further the beam penetrates into the sample. This will cause the resulting image to come from within the material and not from the surface information. A charge will also build up in the sample making the profile nonuniform across the sample.

However, there are pitfalls to operating at lower gun voltages. The lower voltages will result in much lower return signals and therefore have a negative impact on the signal-to-noise ratio. This makes the electron detection efficiency of the system extremely critical. IVS has optimized the system for standard operating conditions at 550 volts. This voltage provides the optimal balance of image quality and charging characteristics. Higher voltages can be easily run on different samples but the high collection efficiency of the system does not require it.

Equally important to the primary beam design is the collection of electrons. Traditional SEM designs call for Everhart-Thornley[3] detectors that are mounted to the side of the final lens pole piece. This creates two undesirable affects on the quality of the image. The first is that the secondary electron collection is not symmetrical. This causes the profiles to be of higher contrast on one side of the feature than the other side. The second issue is that collection of backscatter electrons is almost nonexistent with the Everhart-Thornley detector scheme. Electron detectors with a direct line of site to the electron generation are required in order to efficiently collect and image in a backscatter mode. Utilizing a multiple detector design would therefore create unnecessary complexity to the imaging system.

The use of a micro-channel plate (MCP) detector[4] mounted above the sample solves both of these problems. The MCP is round and completely encircles the primary beam and can be placed directly above the sample. With this technology, the signals are symmetrical and the collection efficiency of both secondary and backscatter electrons is vastly improved. A third benefit of this design is a major improvement in the signal to noise ratio of the SEM image. Reduced amplification of the source signal provides an image that is both clean and of high contrast even at magnifications as low as 100X. High contrast at low magnification is important for robust automation of the CD SEM.

2.2 Measurement Algorithms

As noted earlier, the measurement of the Pole 2 structure requires a suite of dedicated algorithms designed to provide the measurement repeatability, stability and correlation capability required for the TFH process. The final performance of the TFH device is driven not only by the Pole 2 width, but also the degree of necking from zero throat and amount of resist scumming in the bottom of the trench. In order to provide this information, IVS has developed a series of three measurement applications for the Pole 2 process.

Dedicated 'Pole2' Measurement Algorithm: Working in conjunction with numerous TFH manufacturers, IVS was able to develop a dedicated 'Pole2' measurement algorithm which provides the required levels of measurement repeatability, stability and the ability to correlate to the final Pole 2 structure. The measurement algorithm is a modified version of the commonly used Linear Regression algorithm. The algorithm analyzes the image profile to determine the linear fit for the baseline and each side wall. These three lines are then extrapolated to locate the intersection points which then defines Pole 2 width. The variables that define the linear fit to the side wall profile are definable by the user which allows the algorithm to be modified to meet the customers exact resist profile characteristics and correlation to the final Pole 2 dimensions. It should also be noted that each side wall profile is analyzed independently from the other in order to obtain the best fit to the image. This methodology has provided the TFH manufacturer with Precision/Tolerance (P/T) ratios of less than 1.0 % overall and typical performance better than 0.5 %.

Ability to Monitor Pole 2 Necking: A key parameter in the final performance of the TFH device is the amount of necking that exists in the Pole 2 structure as the resist image moves below zero throat (where zero throat is defined as the base of the coil structure). Due to the extreme topographies involved in the photolithography process, resist processing phenomenon make it difficult to control the exact dimension of the Pole 2 structure near zero throat. The amount of change in the critical dimension at different points below zero throat is an important control mechanism for TFH manufacturing. This information can only be determined if the metrology system is able to image the bottom of the resist profile and perform repeatable measurements. By using the CD SEM in conjunction with its ability to perform multiple measurements on the same acquired image, the system can provide a real-time process control mechanism for the Pole 2 necking. This is accomplished by the end user defining multiple measurement gates at different distances below zero throat. Each of these measurements will be output to the user during the run of a production lot through the CD SEM. These measurements can then be utilized to determine the amount of necking that exists for each Pole 2 structure measured. This additional capability has been integrated into the system in a manner that has minimal impact on the overall system throughput. It has therefore provided an additional level of process monitoring at no expense to cost of ownership.

Determination of Resist Scumming in the Pole 2 Trench: The latest algorithm developed for this technology provides the end user with the ability to determine if the Pole 2 trench has resist scumming or if there has been a substantial change in the resist side wall profiles. With the very large aspect ratios common to the TFH process, resist scumming or changes in the resist side walls are very common phenomenon in the Inductive TFH technology. If these issues are not detected during the photolithography process, then the substrates are at high risk for scrap due to issues that will be encountered during the nickel iron plating process. In order to accommodate this metrology requirement, the dedicated 'Pole2' measurement algorithm was expanded to include a secondary set of side wall linear fit parameters. With two sets of parameters now available for the linear fit to the side wall, the Pole 2 structure is measured with both and then a mathematical computation is performed to determine the degree of resist scumming. If the output of this computation is greater than a threshold defined by the end user, the system will report a measurement failure warning the end user that resist scumming is highly probable.

3. RESULTS

The various methods that have been implemented on the IVS-200 CD SEM (as described in Section 2.3) have been the result of many experiments and cycles of learning with leading edge TFH manufacturers. This section will provide some data results form this work indicating the measurement repeatability, ability to detect Pole 2 necking and the ability to monitor the trench structures for resist scumming.

3.1 Measurement Repeatability

The following table shows typical results for measurement repeatability on a TFH Pole 2 sample. The data was taken on ten locations around the wafer. Two measurement features per location were measured. Each measurement was performed in a fully dynamic mode of operation. The definition of dynamic repeatability is that all sites on the wafer were measured once, the wafer was removed from the system, placed in the cassette and reloaded for the next set of measurements. This cycle was repeated five times. Reported are mean, min, max, range, standard deviation, and the number of measurements made. At the bottom of the table we have also reported the pooled standard deviation for this set of measurements.

MR Top-Pole

Die #	Site #	Mean	Max	Min	Range	S(N-1)	N
1	1	3.209	3.215	3.202	0.013	0.0040	5
1	2	3.232	3.238	3.227	0.011	0.0040	5
2	1	3.500	3.355	3.345	0.010	0.0037	5
2	2	3.347	3.360	3.336	0.024	0.0066	5
3	1	3.285	3.290	3.278	0.012	0.0038	5
3	2	3.324	3.330	3.319	0.011	0.0040	5
4	1	3.130	3.138	3.123	0.014	0.0046	5
4	2	3.101	3.111	3.093	0.018	0.0055	5
5	1	3.129	3.141	3.123	0.018	0.0054	5
5	2	3.145	3.153	3.141	0.013	0.0041	5

6	1	3.231	3.240	3.218	0.024	0.0070	5
6	2	3.295	3.303	3.290	0.013	0.0036	5
7	1	3.212	3.219	3.203	0.017	0.0051	5
7	2	3.250	3.259	3.240	0.019	0.0063	5
8	1	3.206	3.215	3.198	0.017	0.0046	5
8	2	3.337	3.348	3.330	0.018	0.0052	5
9	1	3.383	3.400	3.372	0.028	0.0077	5
9	2	3.400	3.405	3.390	0.015	0.0050	5
10	1	3.151	3.156	3.144	0.013	0.0033	5
10	2	3.115	3.126	3.108	0.018	0.0067	5

Pooled Std.	**0.0052**

3.2 Detection of Pole 2 Necking

Below is a table of data collected for the purpose of demonstrating the importance of necking measurements. Ten locations on the wafer were measured dynamically five times. At each location, three measurements were made. One measurement was made at 1.5 microns below zero throat, the next was made at a 3.0 micron offset, and the final one was made at a 4.5 micron offset. The data shows necking for each of the ten locations. Site 1, closest to zero throat is consistently the smallest with site 2 and 3 being progressively larger than the last. Note that only with the high repeatability demonstrated can we detect the sometimes subtle necking differences along the pole.

Inductive Top-Pole Necking Data

Die #	Site #	Mean	Max	Min	Range	S(N-1)	N
1	1	4.207	4.219	4.191	0.028	0.012	5
1	2	4.269	4.279	4.262	0.016	0.006	5
1	3	4.330	4.337	4.313	0.024	0.009	5
2	1	4.502	4.520	4.492	0.027	0.011	5
2	2	4.559	4.568	4.543	0.025	0.009	5
2	3	4.585	4.607	4.573	0.034	0.013	5
3	1	3.908	3.916	3.899	0.016	0.007	5
3	2	4.014	4.019	4.004	0.015	0.007	5
3	3	4.107	4.109	4.106	0.003	0.001	5
4	1	4.104	4.116	4.092	0.024	0.010	5
4	2	4.222	4.227	4.217	0.010	0.004	5
4	3	4.301	4.320	4.281	0.039	0.014	5
5	1	4.583	4.595	4.571	0.024	0.011	5
5	2	4.629	4.641	4.618	0.023	0.010	5
5	3	4.702	4.715	4.689	0.027	0.011	5
6	1	4.417	4.427	4.389	0.038	0.016	5
6	2	4.500	4.503	4.497	0.007	0.002	5
6	3	4.574	4.580	4.569	0.011	0.005	5
7	1	4.431	4.433	4.430	0.004	0.002	5
7	2	4.493	4.497	4.479	0.018	0.008	5
7	3	4.507	4.526	4.500	0.027	0.011	5
8	1	4.061	4.067	4.054	0.012	0.006	5
8	2	4.175	4.179	4.172	0.007	0.003	5
8	3	4.257	4.260	4.253	0.007	0.003	5
9	1	4.605	4.615	4.586	0.028	0.011	5
9	2	4.691	4.692	4.687	0.006	0.002	5
9	3	4.753	4.765	4.735	0.029	0.014	5
10	1	4.380	4.398	4.372	0.026	0.010	5
10	2	4.450	4.468	4.439	0.029	0.011	5
10	3	4.521	4.529	4.499	0.030	0.013	5

Site #	Average	Pooled
Total	4.395	0.009
1	4.320	0.010
2	4.400	0.007
3	4.464	0.010

3.3 Detection of Pole 2 Resist Scumming

An feasibility study was conducted to determine if the CD SEM could be utilized to detect and predict that resist scumming exists at the bottom of the Pole 2 trench structure. This study utilized a sample that had been slightly underexposed in order to create a sample that contained Pole 2 trenches with and without resist scumming. A jobplan was created to measure a total of twelve Pole 2 features of which four where known to exhibit resist scumming. The modified 'Pole2' algorithm was utilized to collect both the track width and the determinant for resist scumming. The mathematical computation was calculated and a prediction was made as to whether resist scumming existed. A sample plot (the y-axis has been normalized for presentation in this paper) is provided in Figure 3 below. It should also be noted that each of the twelve Pole 2 features was measured at three different distances below zero throat to test the prediction capability within a single pole.

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A visual comparison was then performed whereby each of the twelve Pole 2 features was visually inspected to quantify the level of resist scumming. This information was cross correlated to the data plot in Figure 3 from which it was determined that the methodology correctly detected the resist scumming 100% of the time. This test was repeated across a series of samples and Pole 2 structures with a greater than 99% success rate.

4. DISCUSSION

It has been demonstrated in this presentation that recent advances in the resist processing technology of the TFH industry are driving a stronger need for next generation metrology applications and systems. The first step in this process was demonstrated with the implementation of the IVS-200 CD SEM Metrology System in numerous leading edge TFH manufacturers. The CD SEM technology has provided the TFH manufacturer with an ability to image the true bottom of the resist feature with the required measurement repeatability, stability and capability to correlate to the final Pole 2 structure.

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