OPTICAL WAVEGUIDE MATERIALS FOR HEAT-ASSISTED MAGNETIC RECORDING (HAMR)

Increasing the capacity of mainstream data storage devices is crucial to supporting the continued growth of the worldwide datasphere. With the shift to "cloud" storage as the preferred medium, the adoption of very high capacity hard drives requires drive makers to keep pace by increasing the storage density of recorded information on disc surfaces. Seagate's **Dr. Xiaoyue P. Huang** and **Dr. Michael C. Kautzky** explain how thin film technology has helped pioneer the introduction of new drive technology, Heat-Assisted Magnetic Recording (HAMR), to provide a commercially viable path beyond the density limits of today's perpendicular magnetic recording.

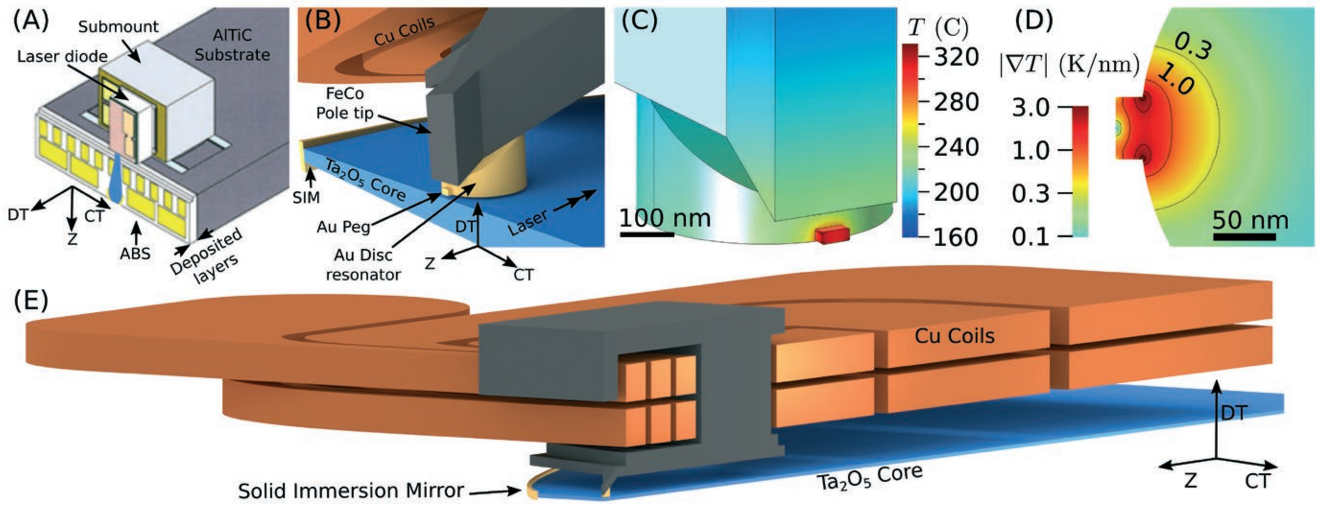

Figure 1: Overview of a HAMR Writer. (A) Recording head at 30X magnification. Approximate dimensions are 1.2 mm Down Track (DT), 700 um Cross Track (CT) and 100um in z. Note the direction of the waveguide core (blue). Media moves under the head in the +DT direction. (B) Zoomed version (30KX) of the head showing the near field transducer (gold), magnetic pole tip (gray), copper coils (orange) and tantala core (blue). (C) Temperature of the Near Field Transducer and Pole given an input power of 15mW (assuming 100% efficiency for the laser and light delivery system). (D) Cross section of the NFT showing the in-plane thermal gradients (E) Cross section through writer core, coils, NFT and solid immersion mirror (SIM).

To adapt to HAMR-specific data writing, recording heads in the drive are modified to be able to deliver thermal and magnetic spots <30nm to the media surface, and to modulate this process at data rates exceeding 1 Terabit/second. This is achieved by integrating a solid state laser, a thin film optical waveguide and a new nanofocusing near-field transducer ("NFT") into the head (Figure 1). During recording, near-IR laser light from the back of the head is collected by an optical input coupler and propagated down the waveguide where it is focused to illuminate the NFT. The incident light energy is converted into oscillations of surface free electrons in the NFT metals (called "plasmons"), and the associated electric field is then focused with a disc-facing antenna to heat the high-coercivity FePt recording layer above its Curie temperature. Using the magnetic field from a high-moment write pole in very close proximity to this heated spot, magnetic transitions are recorded and "frozen in" to the media layer during cool down, providing high recording densities with excellent thermal stability (Figure 2).

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Critical to the success of the new head components is their ability to meet both drive performance and reliability specs simultaneously (e.g. capacity, data rate, and cumulative failure rates of <1% at average data writing workloads over a 5-year period).

A major challenge here is that the operating conditions of the HAMR head during recording are extreme: >300°C peak temperatures, power densities in the NFT of ~150 TW/m^2 (which is ~25X higher than the sun), thermal gradients >1K/nm, pressures >10 atm (similar to a locomotive steam boiler) and an oxidative environment. Many conventional recording head materials fail under these conditions through a wide range of diffusion, phase change, chemical reaction and stress-related mechanisms. Indeed, initial HAMR head lifetimes were in the ms range due to poor durability. However, we have now addressed this through development of new thermally stable functional thin film materials across multiple functions. Examples include oxides for low loss optical transmission (which are the focus of this article), new transition metal alloys with engineered microstructure for efficient field confinement and high thermal conductivity, adhesion promoters for metal-dielectric interfaces, hard mask materials for sub-40nm nanoscale patterning and new diffusion barrier/heat sinking materials. These material innovations, together with improvements in design efficiency, downstream machining and test control, have enabled us to mitigate the HAMR-specific failure modes and increase mean HAMR head lifetimes from milliseconds to hundreds of hours, enabling launch of the industry's first HAMR 20TB drive.

During HAMR operation, the laser light needs to be carried from diode to NFT through a waveguide structure which is composed of a core and surrounding claddings. High-quality optical waveguide materials with low propagation loss are required to minimize the laser power required and avoid undue internal heating. Reactive PVD is the

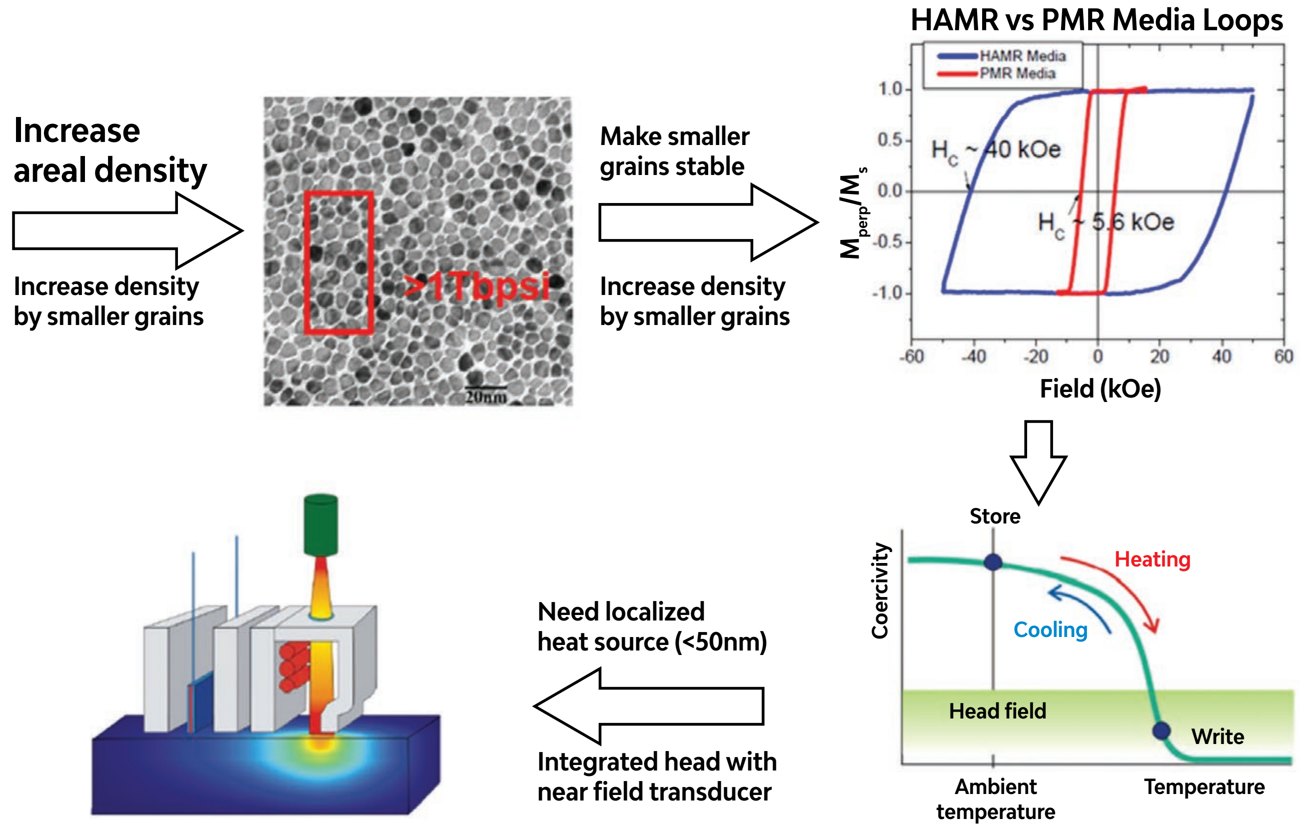

Figure 2: HAMR Recording Process.

favored technique to achieve this, providing high density amorphous films at reasonable deposition rates and low impurities at temperatures below 300°C (needed to avoid damage to the read sensor). For optical core layers, materials with index n > 2 are desirable for light confinement. HAMR development has focused on metal oxides, specifically d-band oxides such as Ta_2O_5 (n~2.1) which deposit in an amorphous state but with crystallization temperatures that typically exceed 800°C, reducing the risk for irreversible propagation loss increase

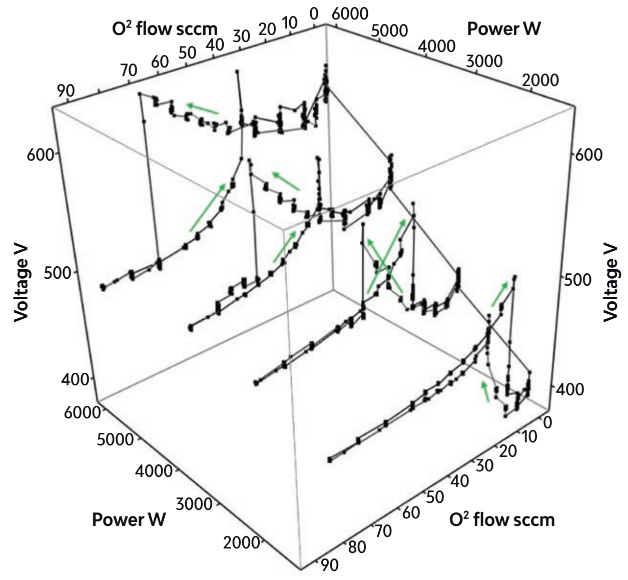

Figure 4: Hysteresis in r-PVD Ta_2O_5 at 200°C.

during service life of the head. Other oxides such as TiO_2 were also explored because of the high refractive index (n > 2.3) increasing the optical delivery efficiency. Such oxides also present the best resistance to chemical attack from wafer-level patterning and to ABS reaction during operation.

Robust waveguide core films are readily produced on Evatec's CLUSTERLINE® 200 PVD platform (Figure 3).

The reactive hysteresis map of a Ta_2O_5 process is shown in figure 4. As the cathode power increases, voltage vs O_2 flow hysteresis flips the polarity (indicated by the green arrows). This flexibility provides a wide process window for balancing deposition rate, particle generation and material stoichiometry. Films with optical loss less than 1dB/cm and less than 1% within-wafer sigma of Ta_2O_5 at deposition rates > 100 Å/min can be achieved on 200mm wafers in DC sputtering module. Similar reaction behaviors are also found in other high-n refractive metal reactive process, e.g. Ti.

"Conditions inside the HAMR head are challenging – with power densities 25 times higher than the sun"

TiO_2 is another attractive high refractive index material candidate which has also been studied in this system. A high purity 300mm Ti target was used with pulsed DC power during reactive sputtering in an Ar:O_2 mix. The

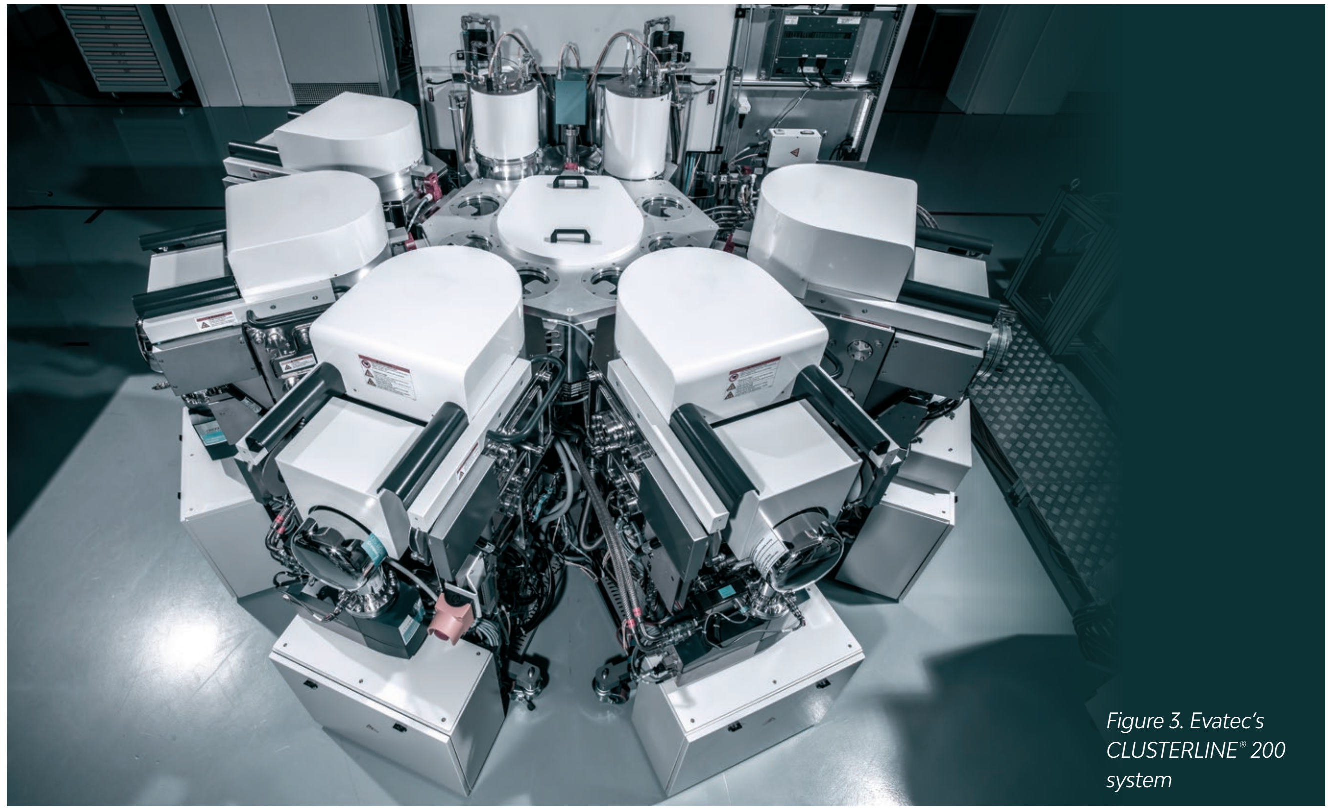

Figure 3. Evatec's CLUSTERLINE® 200 system

process was tuned to poison mode with sufficient O_2 flow in order to provide a stable and uniform low optical loss TiO_2 film on 200mm wafers (Figure 5)

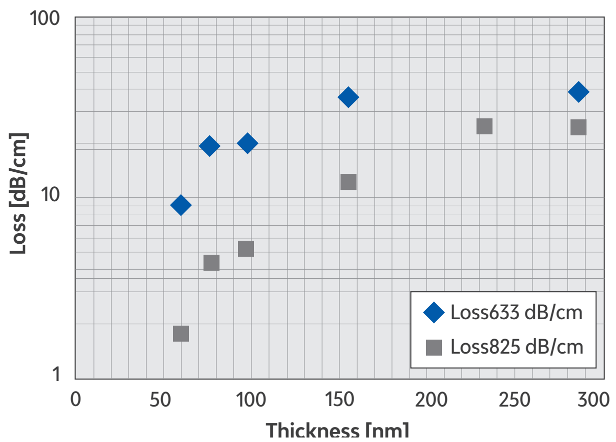

Figure 5: Optical propagation loss of r-PVD TiO_2 films.

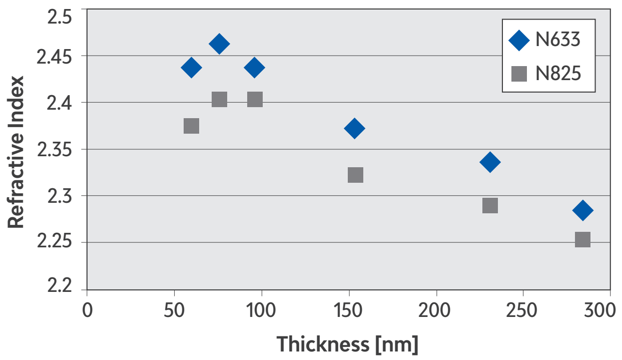

Figure 6: TiO_2 refractive index vs thickness.

At a substrate temperature of 200˚C, the optical propagation loss of the sputtered TiO_2 films increased as the film thickness increased. This trend was the same for both 633nm and 825nm wavelengths, with losses below 40dB/cm and 25dB/cm respectively up to 285nm film thickness. Film index maxima over 2.4 were achieved between 50-100nm but declined to 2.25-2.3 at higher thicknesses (Figure 6).

The cross-section TEM images for a 143nm TiO_2 film revealed enlarged crystalline grain structure beyond ~54nm thickness when grown on amorphous SiO_2 substrates (Figure 7). The top part of the film also became more porous and rough with clear pinholes between grains. By contrast, the initial 50nm of TiO_2 film was more homogeneous. This deterioration of material quality at high thicknesses was consistent with the optical loss and refractive index trends.

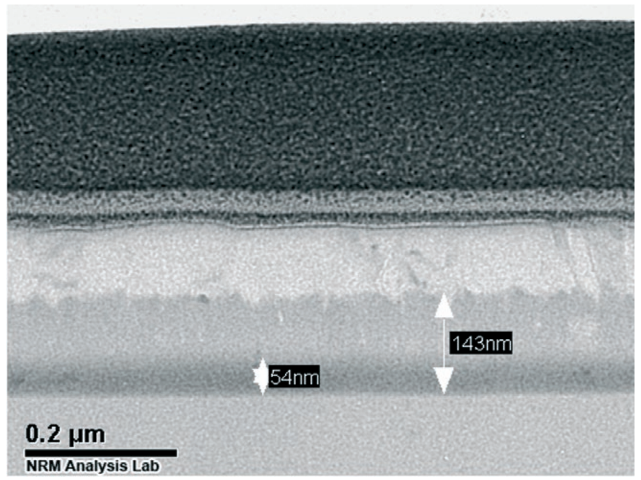

Figure 7: Cross-section TEM of r-PVD TiO_2 film.

To achieve high index TiO_2 films with low optical loss, composite layer films were developed (US Patent 8,681,595) by utilizing two process chambers in the CLUSTERLINE® system. The new TiO_2/Ta_2O_5 multi-layer films engineered very thin, sub-5nm Ta_2O_5 layers to break the crystalline growth of TiO_2 material. As shown in figure 8, the new film structure presented amorphous and uniform morphology.

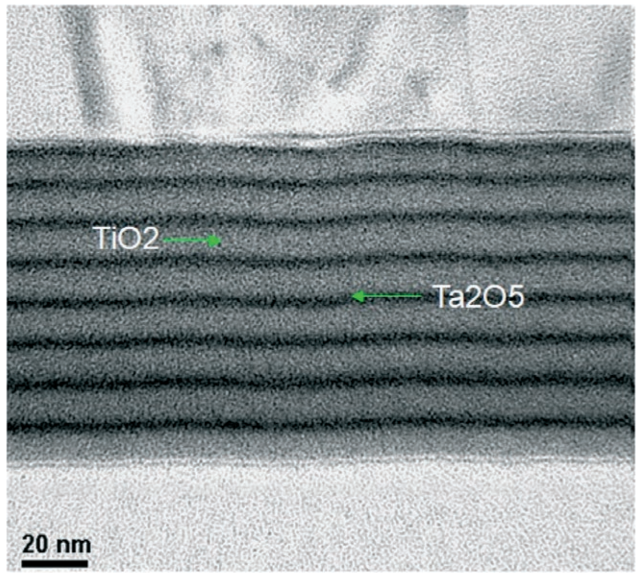

Figure 8: Multilayer TiO_2/Ta_2O_5 films with fully amorphous structure.

The composite layer films exhibited over tenfold lower optical waveguide losses (Figure 9), which are below 2dB/cm at 633nm and 825nm wavelengths. In addition, the refractive indices of multilayer films maintained n > 2.30 for all thicknesses, making them viable as an ultra-high index core material candidate.

Well controlled reactive sputtering processes have shown themselves capable of producing the high quality films of high-index oxide materials required for HAMR recording head waveguides.

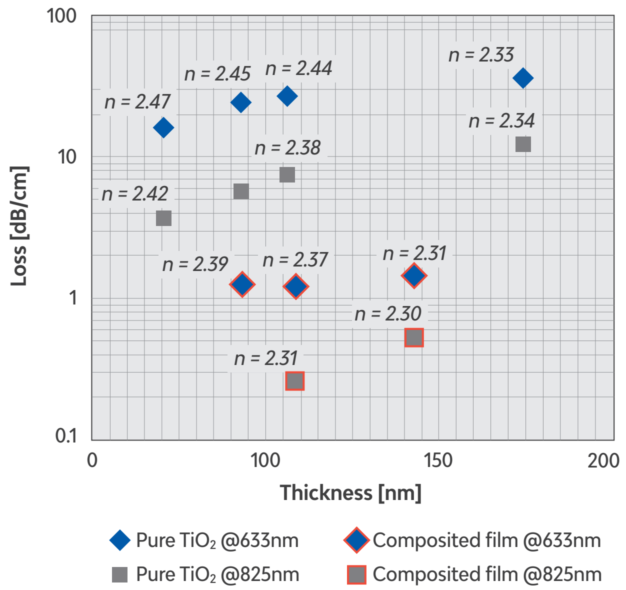

Figure 9: Optical loss and refractive index vs thickness for multilayer TiO_2/Ta_2O_5 films.

About the authors

Xiaoyue Phillip Huang is a Senior Staff Engineer of the HAMR Writer Process Development group at Seagate Technology. With Ph.D. degree in Engineering Physics, Dr. Huang joined Seagate's Recording Head Division in 2007. He played a key role as a thin film process specialist and technical lead in optical and dielectric materials for the cutting edge HAMR technology development. He is a holder of 24 issued US patents and 12 Seagate trade secrets.

Michael Kautzky is the Managing Technologist of the HAMR Writer Process Development group at Seagate Technology. Dr. Kautzky holds a Ph.D. in Materials Science and Engineering from Stanford University. He has been with Seagate's Recording Head Division for 24 years with technical and management work in the areas of advanced thin film materials and deposition development, wafer-level recording head integration, and novel thin film characterization. He is a holder of 115 issued US patents. Dr. Kautzky's group's current focus in on novel materials development and wafer integration for next generation heat-assisted magnetic recording heads.

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Did you know?

In April 2021 Seagate announced it was the first company to ship a cumulative storage capacity of 3 Zettabytes of storage since its foundation.

That's equivalent to 1.5 quadrillion selfies, or 197,308 selfies for every person on earth (a quadrillion = 10^{15}).

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