Optical Storage Disk Technology

Richard J. Gambino, Guest Editor

Optical storage of digital information has reached the consumer market in the form of the compact audio disk. In this technology, information is stored in the form of shallow pits embossed in a polymer surface. The surface is coated with a reflective thin metallic film, and the digital information, represented by the position and length of the pits, is read out optically with a focused, low-power (5 mW) laser beam. When used for information storage for a computer[1] this device is called a CD-ROM, a Compact Digital-Read Only Memory. The user can only extract information (digital data) from the disk without changing or adding any data. That is, it is possible to "read" but not to "write" or "erase" information.

While it is an advantage to have permanently stored information in some cases—for example when listening to Beethoven's Ninth Symphony—in other situations the read-only feature is not appropriate. For most computer applications, it is essential that the user be able to store information on the disk and read it back at will. For example, in a word processing task—such as typing this article—it is often necessary to store the document on a disk. Optical data storage for this purpose is available in the form of a Write Once Read Many times (WORM) optical disk drive. The operating principle in a WORM drive is to use a focused laser beam (20 - 40 mW) to make a permanent mark on a thin film on a disk.[2] The information is then read out as a change in the optical properties of the disk, e.g., reflectivity or absorbance. These changes can take various forms: "hole burning" is the removal of material (typically a thin film of tellurium) by evaporation, melting or spalling—sometimes referred to as laser ablation; bubble or pit formation involves deformation of the surface, usually of a polymer overcoat on a metal reflector.[3]

Returning to the example of storing text information, it might be necessary to change some stored information to correct errors or make other revisions. With a WORM optical disk, since data already written cannot be erased, the only option is to write the new data on the disk with the corrections. The system software, called an Optical Disk File System, will compare the old and the new data so that only the changed portions need to be rewritten. The software also records the location of the updated data in a separate part of the disk reserved for directory information. This procedure is designed to reduce the cost in both storage space and access time associated with WORM-type optical disks. The impact on access time comes about because the system must read each cancellation message to find the location of the most recently stored version of the text.[4] Furthermore, having a digital copy of earlier drafts is of no particular advantage for word processing tasks. (A counter example is financial records where the inability to erase information could be a distinct advantage for auditing purposes.) In any case, the computer industry has grown up with fully erasable magnetic storage so only erasable optical disks can compete in many applications where magnetic storage is presently used. This is particularly true in large systems where access time may be as important as density and the longer access time of optical disks is compounded by the search through the locations of old records in a WORM file.

Although the CD-ROM and WORM formats have been successfully developed and are well suited for particular applications, the computer industry is focusing on erasable media for optical storage. There are two types of erasable optical media: phase-change (PC) and magneto-optic (MO). Both will be detailed in this issue of the *MRS BULLETIN* in "Magneto-Optical Storage Materials" by Frans Greidanus and Bas Zeper and in "Multilayered Thin-Film Materials for Phase-Change Erasable Storage" by Matthew Libera (also Guest Editor for this issue) and Martin Chen.

Magneto-Optic Media

In MO storage, a bit of information is stored as a $\sim 1 \mu m$ diameter magnetic domain, which has its magnetization either up or down. The information can be read by monitoring the rotation of the plane of polarization of light reflected from the surface of the magnetic film. This rotation, called the Magneto-Optic Kerr Effect (MOKE) is typically less than 0.5 deg. The materials used for MO storage are generally amorphous alloys of the rare earths (RE) and the transition metals (TM), Fe or Co. Amorphous materials have a distinct advantage for this purpose because they do not suffer from "grain noise," spurious variations in the plane of polarization of reflected light caused by randomness in the orientation of grains in a polycrystalline film.[5] It is also possible to modify the properties of these materials over a wide range by alloying or by varying processing conditions.[6] Because of these advantages amorphous alloys are used as the medium in all existing commercial erasable optical disks. Active research programs are in progress on sputtered garnet films and metal multilayers, since these materials have significantly better corrosion resistance than the RE-TM films.

The data track on a magneto-optic disk must be initialized by magnetizing it all in one direction. Bits are written by heating above the Curie point, T_c, and cooling in the presence of a magnetic field. This is known as thermomagnetic writing. The coercive force, the effective field that keeps the domains in place and stable in size, decreases with increasing temperature as T_c is approached. The applied magnetic field used to switch the magnetic domain is set at such a magnitude that it can only overcome the coercive field and saturate the material when it is heated to a temperature close to T_c. Thus all the other domains are unaffected by the field because, at the ambient temperature, the coercivity is much higher than the applied field. The electromagnet providing this applied field need not be close to the medium or have small pole tips as in a magnetic head because it is the heated spot, not the geometry of the magnetic head, that defines the size of the written bit. The primary component parts of an optical data storage system are shown schematically in Figure 1.

Phase-Change Media

In the phase-change materials, information is stored in regions that are different phases—typically amorphous and crystalline. These films are usually alloys or compounds (e.g., GeTe) of tellurium which can be quenched into the amorphous state by melting and rapidly cooling. The film is initially crystallized (the as-deposited film is amorphous) by heating it above the crystallization temperature T_x. In most of these materials T_x is very close to the glass transition temperature T_g. When the film is heated with a short (10–20 ns), high-power, (20 mW) focused laser pulse, the film can be melted and quenched to the amorphous state. The amorphized spot can represent a digital "1" or a bit of information. The information is read by scanning it with the same laser, set at a lower power, and monitoring the reflectivity. The amorphous alloy usually has a lower reflectivity than that of the crystallized alloy. Erasure is accomplished by heating the amorphous spot above T_x long enough to crystallize it. The same laser is used but at a lower power and, if necessary, for a longer time than in writing.

Issues this technology must address are the long erase time required with most media and the limited number of reversible read-write cycles that the media can survive. On the other hand, PC media have high intrinsic signal-to-noise ratios and they do not require the complex polarized light optics detection system needed for MO systems.

Features in Common

What features do all optical disks have in common? They all use diffraction-limited optics; that is, the smallest spot size will be limited by and approximately equal to the wavelength λ of the laser light used. Actually, the diffraction limit is $K\lambda/NA$ where NA is the objective lens numerical aperture and K is a constant of order unity. The areal density (bits/cm^2) is approximately given by $(NA/\lambda)^2$.[2] A simple storage scheme might use a written spot to represent a binary "one" and the absence of a spot to represent binary "zero." In practice, more complex coding schemes are used, involving the positions of transitions along the track. This gives somewhat higher density and has advantages for implementing error correction codes. Irrespective of the coding scheme, the minimum spacing along the tract is set by the laser wavelength.

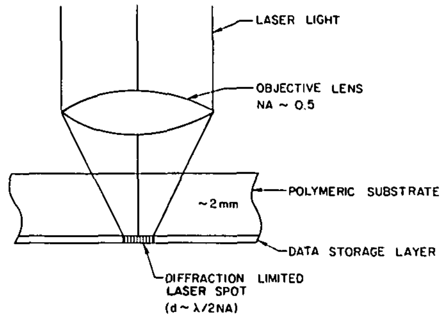

Figure 1. Schematic illustration of the primary elements of an optical data storage system.

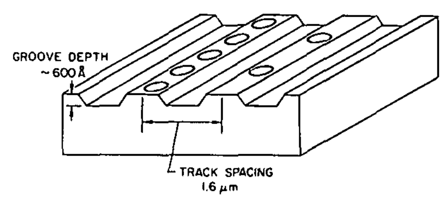

Figure 2. Geometry of the tracks used in optical data storage.

In most storage media the tracks are physically defined in the disk when the disk is fabricated. (See "Trends in Optical Disk Mastering" by Paul Put in this issue.) The track spacing is gated by optical lithography and the control tolerance of the fabrication process (Figure 2). The current lower size limit of 1.6 μm has been adopted as an industry standard for CD-ROMs and is being considered for adoption by standards committees on WORM and erasable disk products.[7] These tracks provide a "tracking" optical signal which is used to keep the head over the data. Some type of track-following scheme is common to all optical storage systems, and the high track density (tracks per inch along the disk radius) this makes possible is an important factor in the high storage density of optical systems. The density along the track of magnetic recording can be as high or higher than present optical products but the tracks in magnetic recording are much wider.

A second feature all optical storage systems have in common is the light source—the semiconductor laser. The main difference from one type of system to the other is the maximum power level needed, from 5 mW for CD-ROM to 20–40 mW for WORM, MO, and PC. Since the storage density is determined by the wavelength, one of the factors determining the extendability of this technology to still higher density is the availability of a compact light source. For example, 670 nm semiconductor lasers are currently available, but only with demonstrated reliable operation up to 5 mW of power. Read/write experiments with research-grade higher power semiconductor lasers of this wavelength have shown that about a 50% increase in areal density[8] is possible but these lasers are not yet commercially available.[9] Shorter wavelength lasers for this application will probably be available soon. Note that, for a given power density, less power is needed at shorter wavelengths because the light is focused on a smaller area.

Much progress has been made recently in a new approach to 473 nm light by frequency doubling light from a GaAlAs semiconductor laser.[10] (See the front cover of this issue.) It has also been shown that this process (using nonlinear optic materials) can be efficient enough to produce 21 mW of doubled light from a 63 mW semiconductor laser source.[11] The payoff—in terms of a factor of four increase in areal density—is a strong incentive to try to make these frequency doubling schemes work in a practical device.

Laser reliability will continue to be a key concern in future systems. Facet damage limits reliability at high power so within the constraints of data stability, the lower the writing threshold power the better.

It is possible to improve the media to lower the threshold power to write. The media can be made with an antireflection coating, a dielectric layer of thickness $\lambda/4$ so that there is destructive interference of the light. The light reflects back and forth in the dielectric, as a standing wave, so that it is efficiently absorbed. One problem with this technique is that if the antireflection coating is too nearly perfect, not enough light is reflected back to read out the written information. The signal level in the detector must at least exceed the shot noise (thermally induced noise) of the detector.

Another way to lower the laser power required for writing is to lower the temperature rise required to write. In the MO media this means lowering T_c; with PC media the controlling factor is the crystallization temperature, T_x. There are, of course, limits on how far this approach can be pushed. If T_c or T_x is too low, the data will not be stable over a wide range of ambient temperatures, for example, a hot day in August.

Gas lasers or optically pumped solid state lasers are not a viable alternative. They are all too massive to be incorporated in the read/write head, but it might be possible to use an optical fiber to bring the light to the head. Even so, it is hard to beat the low cost, long life, and low failure rate of injection lasers. Furthermore, a large laser would have a significant impact on the volumetric density (bits/cm^3) of the system. Optical storage systems generally have a lower volumetric density than magnetic storage systems because the optical head, at present, cannot be compressed in the vertical direction. Magnetic heads are very flat so that about 8–10 magnetic disks can be stacked in the same space as one optical disk. The result from the user's point of view is a comparable number of Mbytes in the same volume. The problem of reducing the form factor of the optical head is formidable. An integrated optics head has been proposed and holds promise not only for a better form factor but also for faster access times. The large mass of the present optical head makes it difficult to move quickly from one track to the other when conducting a random access search.[12] However, construction of an integrated optical head will be a challenge to both the optics and the materials science communities. (See "Materials Challenges in Integrated Optical Recording Heads" by Laura A. Weller-Brophy, Brian J.J. Zelinski, and Dunbar P. Birnie III in this issue.)

Advantages of Optical Storage

One of the major advantages of optical over magnetic storage is that high density optical media are removable while high density magnetic media are not. This arises from the difference in "flying height" of the two technologies — the distance from the head to the moving surface of the medium. In optical storage, the information is read optically through a transparent substrate. The objective lens is typically about 2 mm from the active medium with about 1 mm of substrate between. The objective lens has a high numerical aperture (NA≡diameter/2 × focal length), which means the light is strongly convergent as it passes through the substrate, as illustrated in Figure 1. The result is that scratches, dust particles, and other optical imperfections on the disk's surface are out of focus and thus do not produce a strong noise signal. The disk must be very uniform and free of optical birefringence, as discussed in "Birefringence Properties of Polymeric Substrate Materials" by Ramish Pisipati, Helmut Schmid, and Günther Kämpf in this issue). Because of the relative insensitivity to surface defects the medium can be removed from the disk drive and need only be handled with reasonable care, as with a CD audio disk.

In contrast, the head in magnetic recording must fly over the medium at a height of a few thousand angstroms in order to have a viable signal-to-noise ratio. The flying height will have to become ever smaller as the density increases because smaller bits have less magnetic flux with a smaller radial extent. Magnetic media, therefore, must operate in an ultraclean, dust-free environment because a particle of dust on the disk can cause the head to crash. A head crash not only causes failure of the device but also may cause loss of the stored data.

At the density of an optical disk, it can often be more costly to reproduce the data than the hardware. Consider that it would take about six years of work, typing 20 words per minute, to fill a 700 Mbyte optical disk.

The reliability of optical storage has made backup of magnetic media one of its first applications. The fact that optical disks can be removed, stored, and transported for use on another computer are also big advantages. Magnetic hard disks, of course, can be backed up by saving the data on removable media. There are a number of tape products for this purpose and several optical (disk and tape) products are being marketed for this application. This type of system offers the fast access time of magnetic storage with the reliability and storability of optical. However, this use of optical storage does not take advantage of the random access feature, and if the access time of optical storage can be improved it might make sense to go directly to optical media.

Materials Needs

There are many materials related problems in optical storage technology. Improved media for MO and PC systems with long life and high signal-to-noise ratios at shorter wavelengths will make it possible to extend this technology to higher densities. Short wavelength semiconductor lasers and efficient nonlinear optics materials will lead to compact, high-power light sources. Polymers with low birefringence, that can be fabricated to high dimensional tolerance, are needed for low cost substrates. Optical storage will certainly have a role in future data storage systems. The extension of this technology to still higher density and speed performance will depend on the resolution of these materials issues.

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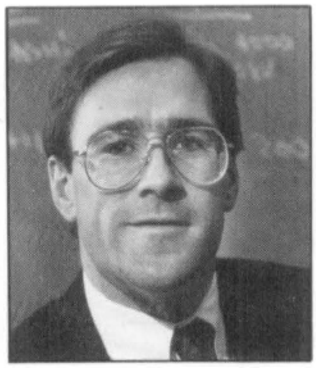

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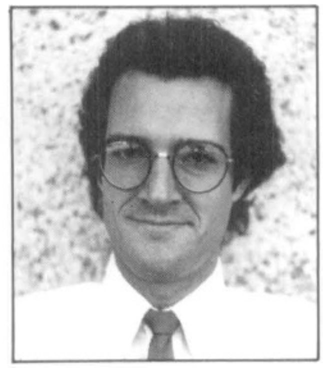

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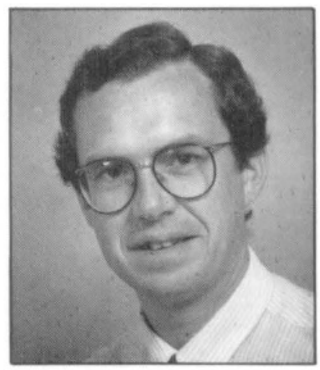

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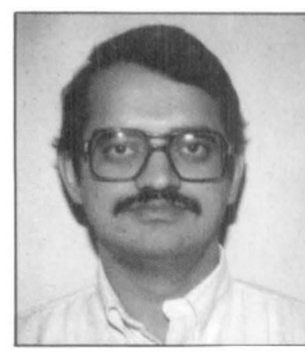

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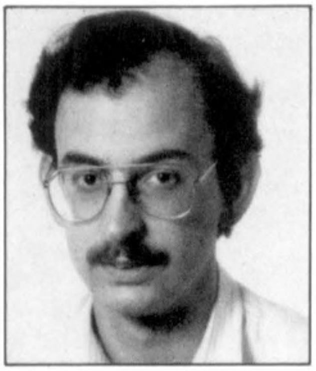

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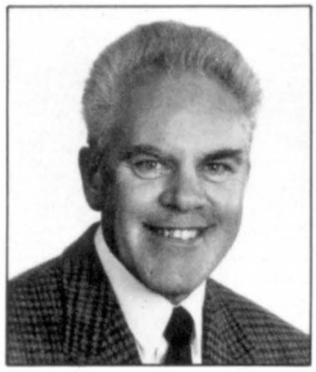

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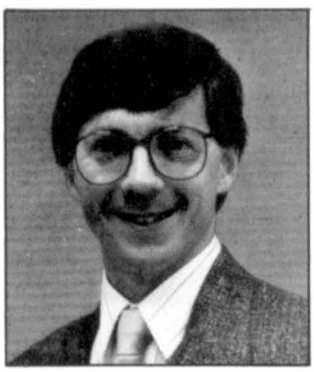

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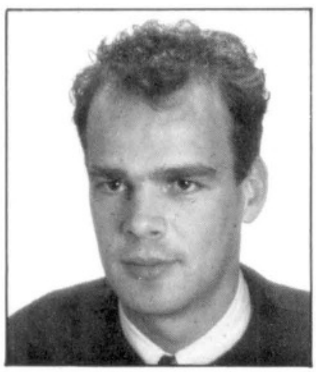

W. Bas Zeper

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