Reading by Laser

The State of the Art and Future of Optical Storage Media

Uli Franz and Wilfried Haese, Leverkusen/Germany

Developments in optical storage media are continuing unhindered. Polycarbonate holds an undisputed position as the material for the substrates of all the systems marketed to date.

The age of digital music storage began in 1982 with the European launch of the audio CD by Philips and Polygram. The new audio media provided stereo sound with a hitherto unachieved hi-fi quality, realised by a data reading technology based on laser technology.

Ten years later, the CD-ROM was introduced, with a format that was ideal for distributing computer programs and games: With its capacity of 650 megabytes, equivalent to more than 450 floppy discs, the CD-ROM became the medium for distributing computer data.

The introduction of the photo-CD, by contrast, was fraught with problems. It was launched at the start of the 90s by Kodak as a writeable CD for digital storage of photos, but the very high price of the hardware and discs proved unacceptable. It was not until recently that the disc now known as the CD-R achieved its breakthrough. Thanks to an improved cost efficiency and compatibility with installed CD-ROM drives, it has become the ideal medium for data storage. The rewriteable CD-RW also raised high expectations, but because of the higher cost for the discs and its limited compatibility with already installed CD-ROM drives, it has stayed in the shadow of the CD-R.

The introduction of the DVD (digital versatile disc) in 1996 represented a further leap in technology. It was driven by the film industry, which required a higher capacity disc. The seven times higher storage density of the DVD, combined with a new software compression pro-

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cess, allows digital storage of movie films with audio tracks in several languages and excellent image quality. Now, a DVD-ROM is also available for computer data, a DVD audio for even higher quality music, and writeable and re-writeable systems (DVD-R, DVD-RAM, DVD+RW and DVD-RW) will follow.

Different Disc Formats have Different Structures

The aforementioned disc formats, in particular the pre-recorded discs (audio, video and ROM), have completely different structures and are therefore manufactured differently from write-once CD-R discs and from the multiple writeable discs (-RW, +RW, -RAM) (Fig.1). Pre-recorded discs, whose content can no longer be changed, carry digital information in the form of indentations in the substrate material. These indentations, called pits, are produced by injection moulding. This provides an unimaginable speed of data transfer to the disc. In the manufacture of a DVD, this data transfer rate reaches 1 gigabyte (GB) per second.

The manufacturing process includes processing the information into digital data, manufacture of a matrix in which the data are transferred in a photographic process, and reproduction of this structure in the 1.2 mm thick polycarbonate disc by the injection moulding process. Then the information-carrying side of the disc is metallised by aluminium sputtering and provided with a protective lacquer coat and multicolour print.

Write-once discs, by contrast, contain virtually no information in their starting state. Instead of the pits, they have a groove structure comparable to the grooves of a gramophone record. These grooves are also embossed into the substrate material by injection moulding are used for guiding the laser beam on the disc. Onto this structured surface, a dye system, comprising, for example, cyanine or phthalocyanine dyes, is applied from solution. After the solvent has evaporated, metallisation step is also carried out. However, unlike pre-recorded systems, gold or silver must be used because of the higher reflectivity. A protective lacquer and, if required, multicolour print is then applied. The pulsed laser beam in the burner writes the digital information into the dye layer, changing its optical properties irreversibly.

Re-writeable discs are relatively similar to write-once discs, however they do not have a dye layer but a layer of a special metal alloy. During writing, the laser changes the phase of the alloy from the crystalline to the amorphous state, changing its reflectivity. To erase the information, the amorphous region is recrystallised. This is achieved by means of carefully controlled laser pulses which control the heating and cooling phases.

Some re-writeable discs, MO discs, use the magneto-optical Kerr effect for writing and reading. The best known of these is the MiniDisc, which requires a special MO player, and is therefore incompatible with the other formats. Although MO discs are technically excellent, offering virtually unlimited rewriting and very high data security, their incompatibility and the higher price level compared to CD/DVD formats has resulted so far in a limited market response outside Japan.

DVDs have a similar layer structure to the CD formats, though the disc consists of two 0.6 mm layers bonded back to back (Fig. 2). It thus allows several information layers to be realised on one DVD. DVD can have capacities from 4.7 GB (one information layer), 9 GB (dual layer), 10 GB (2 layers, front and reverse side) and 18 GB (2 dual layers on the front and reverse sides).

Demands on the Substrate Material

The main component of all optical storage media is the substrate material. The engineering polymer polycarbonate (PC) was invented in 1953 almost simultaneously by H. Schnell at Bayer AG and D.W. Fox at General Electric Comp. Polycarbonate has high transparency, toughness and heat resistance. The material has a particularly well balanced range of properties, including low water absorption, good electrical insulation, sterilisability and problem-free recycling. This makes polycarbonate the ideal material for a wide range of technical applications.

The development of the audio compact disc opened up a completely new application. The main criterion here is the faithful reproduction of pits and grooves on a microscopic scale, which must remain stable for years under extreme conditions. The specially developed, easy-flowing polycarbonate grades meet these requirements outstandingly. They do not warp even at high application temperatures, for example in the car, where temperatures of 80 °C are not uncommon. Another criterion that the material must fulfil is an extremely low birefringence, since the laser beam must penetrate the 1.2 mm thick substrate. Low optical distortion is a fundamental prerequisite.

Bayer made a crucial contribution to the success of the optical storage medium by developing a easy-flowing polycarbonate grade, and cycle times of less than 4 s are now possible in CD production, compared with over 20 s at the beginning of the eighties. The introduction of the DVD with half the substrate thickness and reduced pit structures led to a new challenge to polycarbonate manufacturers. Bayer was the first to respond, presenting Makrolon DP1-1265 in 1996, a product specially tailored to DVD production. It offers excellent flow properties, reduced birefringence compared with standard CD-grade polycarbonate, and a wide processing window. Depending on the machine and process, cycle times of below 3.5 s for CD production and about 4.5 s for DVD production are possible.

Alternative polymers, such as polymethyl methacrylate (PMMA) or cyclic polyolefins, which are occasionally mentioned in the literature as potential candidates, do not have a chance in practice. Their less well-balanced combination of mechanical, thermal and chemical properties, for example, leads to longer cooling times, and therefore longer cycle times, which immediately have a long-term effect on the cost structure of the manufacturing process.

Market Trends

It was impossible to predict what a massive growth awaited the CD. From world production of about 20 million in 1984, about 5.5 billion CDs were produced in 1995, corresponding to a polycarbonate volume of about 100 000 t. This was followed by a market trend with 30-% annual growth to about 21 billion discs in 2000 and a material volume of about 350 000 t. These volumes can be subdivided into about 75 % audio CDs/CD-ROMs, 20 % writeable and re-writeable CD/DVD formats, mainly CD-Rs, and about 5 % pre-recorded DVDs.

The future, too, looks very promising. For example, at annual growth rates of about 20 %, the industry is looking forward to a doubling of the optical storage market in 2005 with a consumption of about 700 000 t polycarbonate. More intensive diversification of the systems can be expected in coming years (Fig. 3). While CD audio/CD-ROM were clearly dominant in 2000, these will only show low growth rates in coming years and pass their peak in 2004. Strong growth on the other hand is predicted for writeable and re-writeable CD/DVD formats and pre-recorded DVDs. In 2005, the share of CD audio/CD-ROMs will fall to about 45 %, while writeable and re-writeable CD/DVD formats will increase to

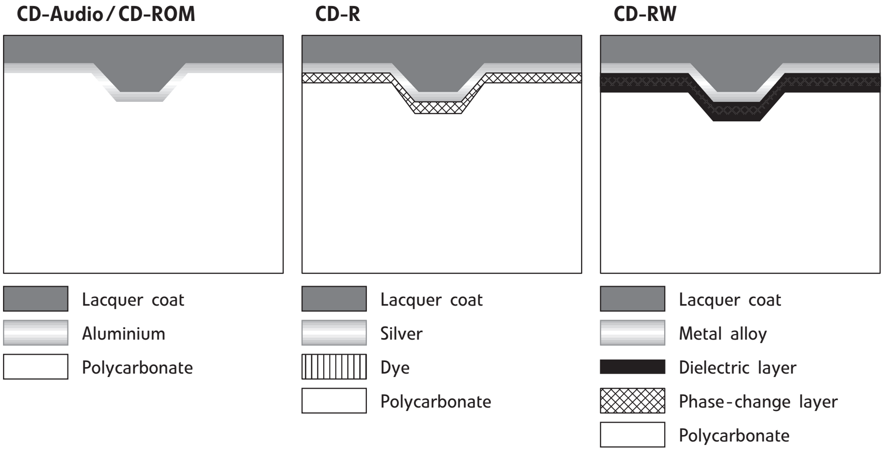

Fig. 1. Schematic structure of pre-recorded, writeable and re-writeable CD formats

30 % and pre-recorded DVDs to about 25 %. The slow growth for pre-recorded CDs is caused by the competition of the Internet as well as the rise of another, related system, the DVD.

Downloading of music and computer programs has become an alternative to purchasing pre-recorded discs in recent years. However, this alternative is severely limited at present by the low availability of the rapid, reliable computer networks and the response of consumers, who prefer to possess music recordings and place them on the shelf. These are all reasons for using cost-effective discs such as the CD-R as back-up media.

Experts assume that it will be possible to achieve sales of the order of 11 billion CD-Rs in 2005 before writeable and re-writeable DVD formats become the media of choice for information exchange and back-up. Although the DVD has been well developed on the market for some time, it has not yet achieved its big breakthrough in terms of volume. The approximately 0.9 billion DVDs produced in 2000 were mainly DVD videos. The development of the DVD-ROM has so far been disappointing. However, it is expected that because of the DVD-ROM drives that have been available in PCs since 1998 and the market introduction of the DVD-compatible game consoles, such as Sony's PlayStation and Microsoft's X-Box, the DVD-ROM will also have a healthy future. Formats such as the DVD-R, DVD-RAM, DVD-RW and DVD+RW are at the beginning of their lifecycle. The low availability of the hardware combined with very high costs for the burners and discs are still standing in the way of rapid expansion. It is very difficult to make predictions for the development of the individual formats. In addition, incompatibilities between individual formats have confused customers. These problems will almost certainly be overcome in the near future and the acceptance of these formats will increase.

Alternative Storage Technologies

The most diverse storage technologies are now encountered on the market, as can be seen in computer systems. The ideal store for small amounts of data that must be rapidly accessed or only temporarily stored remains the microchip, the CPU (central processing unit) of each computer. The hard disc does not allow such rapid access but has a very large data capacity, ideal for storing programs.

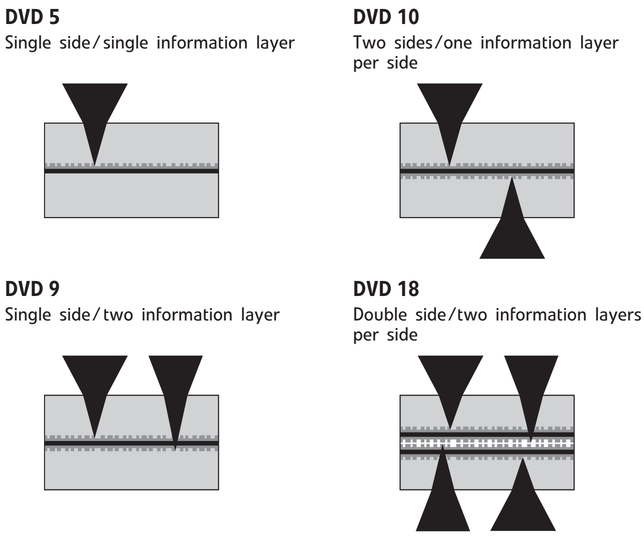

Fig. 2. Schematic structure of DVD formats

Exchangeable media, such as floppy discs, memory sticks or optical discs are used as transfer media for data. The optical disc has the special advantage of a high capacity and relatively fast access time and, because of its high capacity, low price and ease of handling, has become an established platform for data distribution and back up. The ideal storage medium does not yet exist. The search for more efficient systems is continuing. This applies particularly to portable computers, digital cameras and video cameras.

The capacity of a disc is an essential parameter here. Fig. 4 shows the principles for increasing capacity. In the first generation of CD formats, an infrared laser with a wavelength of 780 nm and a relatively weakly focussed pick-up achieves a capacity of 650 megabytes. The information layer was on the reverse side of the CD. The laser beam's path through the polycarbonate was therefore 1.2 mm. With the DVD, the information layer was transferred to the centre of the disc, allowing the use of more strongly focussing optics, which, together with a red laser (650 nm) allowed a storage capacity of 5 GB. If a blue laser (400 nm) were used in the DVD system, the capacity could even be doubled to 10 GB.

In the third generation (DVR), the information layer is located below a 0.1-mm cover layer, virtually at the surface of the disc. This allows even stronger laser focussing, which, together with a blue laser, achieves a disc capacity of more than 22 GB. The next step would be to record the information directly on the surface and focus the optical pick-up even more strongly. With a blue laser, capacities above 100 GB can be achieved with this design. However, effective protection against dirt and scratches is essential to ensure a reliable long-term storage medium. Work is underway on practical solutions.

An increase in capacity can also be achieved by means of a larger number of information layers per disc. An existing solution is the DVD 9, with two layers

(Fig. 2). There are physical limits to realising multiple information layers on a disc, since it is impossible to rule out mutual interference between the information on the different layers. This also applies to the C3D system, in which the read/write process uses the principle of fluorescence and attempts to achieve high capacities by means of a large number of storage layers.

Another concept is to store not only binary zeroes and ones but also other, higher numbers. This requires writing a grey scale, which is then converted into numbers. A system comprising eight grey levels is currently being launched by Calimetrics and TDK. The discs offer about three times the capacity of a CD.

An entirely different concept is to represent information in nanostructures and read them "mechanically". An extremely fine silicon needle scans the surface in the same way as an AFM microscope. However, opinions are divided on the feasibility of using such a system under harsh consumer conditions.

The industry has set great hopes on holographic storage media, in which multiple images can be superimposed at the same place and retrieved independently of one another. This technology could bring inconceivable data densities and transfer rates. Although the main optical components are already available, such as liquid crystal displays that can display images and data or sensors on which virtual images can be projected, so far no material has become available that satisfies all requirements. It should be writeable with a low-power laser beam, heat resistant, and must not degrade over time to avoid read/write errors. Even though large advances have been made in holographic data media, it is not yet clear when the breakthrough will come.

The rapid development in hard discs also deserves mention. The extreme miniaturisation of drives that is now possible is opening up ever more applications and making them ever more competitive. The same applies to chip technology. Here, too, the trend is towards miniaturisation with a reduction in manufacturing costs, which is the main limiting factor in chip storage devices.

There are also many other developments that cannot be discussed here. The intensity of the market struggle is shown by the impressive speed with which such systems can currently be found in digital cameras and video cameras.

Optical storage media have an exciting future ahead. We can still expect many innovations, including many surprises.

The Authors of this Article

Dr. rer. nat. Uli Franz, born in 1964, has been a manager for the optical data storage industry in the strategic marketing of the Bayer AG plastics division, Leverkusen since the end of 2000.

Dr. rer. nat. Wilfried Haese, born in 1953, joined the plastics division in 1989 and is now responsible for optical storage media in the R&D department.

Fig. 3. Lifecycles of optical data storage systems
Anzahl an Discs = Number of discs, Mrd. = bn.

Fig. 4. State and developments in the field of optical data media
Fernfeld = Far field, Nahfeld = Near field, Disc-Kapazität per Schicht = Disc capacity per layer, Wellenlänge = Wavelength, num. Apertur = Numerical aperture, Dicke = Thickness

Fig. 5. Fully automatic adhesive bonding station for assembling substrate halves

Fig. 6. Insertion of a matrix for CD production

Fig. 7. Stacked CDs