A defect management for storage devices is disclosed, which may be used in connection with shingled magnetic recording (SMR). SMR uses bands, consisting of tracks, separated by guard regions. The replacement of a defective sector may be attained by placing a guard region onto the physical location of the defective sector. Depending on the embodiment, the boundaries of the bands and corresponding guard regions may be shifted. The portion of the disk surface which is necessary for the guard regions may simultaneously function as a spare sector area for defective sectors without additional space requirements. In at least one embodiment, an additional guard region reduces the write amplification, and in other embodiments, guard regions are placed onto tracks with an elevated number of primary defects.
FIG. 9

FIG. 10
FIG. 14
FIG. 16
FIG. 20
FIG. 21

FIG. 22
FIG. 27
Start

29 Count defective sectors per track

30 Sort error count in ranking list

31 Set guard track on inner zone boundary

32 Take highest error count from ranking list

33 Check distance and position guard track

34 List empty?

End

FIG. 30
METHOD FOR REPLACING DEFECTIVE SECTIONS ON A DATA CARRIER WITH OVERLAPPING DATA TRACKS AND DEVICE THEREOF

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority from German Patent Application DE 10 2013 022 051.3, filed Dec. 23, 2013, the entire disclosure of which is expressly incorporated herein by reference.

TECHNICAL FIELD

[0002] The present invention relates to the field of data storage, and in particular to a defect management which replaces defective sections on a data carrier surface having overlapping data tracks, such as a hard disk drive, operating according to the shingled magnetic recording (SMR) methodology.

BACKGROUND OF THE INVENTION

[0003] Common hard disk drives are storage devices comprising disks whose data-carrying surfaces are coated with a magnetic layer. The disks are positioned atop one another on a disk stack (platter) where they rotate around an axis, or spindle. To store data, each disk surface is organized in a plurality of circular, concentric tracks. Groups of concentric tracks placed on top of one another in the disk stack are called cylinders. Read/write heads, each containing a read element and a write element, are mounted on an actuator arm. They are moved over the spinning disks to a position over one of the tracks, where the data transfer occurs. The actuator arm is controlled by a hard disk controller, an internal logic responsible for the read and write access.

[0004] Each track on a disk surface is divided into sections or segments known as physical sectors (which must not be confused with the geometrical circle sector). Each physical sector on a track typically stores a data unit of 512 bytes or 4 KB of user data, often referred to as a data block or sector data.

[0005] A disk surface may be divided into zones. Zones are regions wherein each track is divided into the same number of physical sectors; this approach is known as zone bit recording. From the outside inward, the number of physical sectors per track may decrease from zone to zone.

[0006] The storage capacity of a hard disk drive can be increased, inter alia, by reducing the track pitch, respectively the track width, of the concentric tracks on the disk surfaces. This requires a decrease in the size of the read and write elements. However, without new storage technologies, a reduction in the size of the write elements is questionable, as the magnetic field that can be generated is too small to adequately magnetize the individual bits on the disk surface. A known solution is the shingled magnetic recording methodology (SMR), in which the write element writes data tracks in an overlapping fashion.

[0007] The overlapping data tracks are grouped into bands, which are separated by inter-band gaps, also known as “guard bands,” “guard regions,” “guard tracks,” or “guard segments.” To change the content of a track or physical sector in an already populated band, it may be necessary to read out and buffer all subsequent tracks of the band and rewrite the entire buffered data up to the guard region of the band, since the wide write element would otherwise destroy the subsequent track. Due to the sequential and overlapping structure, even a small change to the content stored in the band may result in a significantly increased read and write access. This is referred to as a “read-modify-write” or “write amplification.” Further information pertaining to shingled magnetic recording may be found in U.S. Pat. No. 8,223,458 B2, U.S. Pat. No. 8,432,633 B2, and U.S. Pat. No. 8,179,627 B2 and in patent applications US2012/0082019 A1 and US2013/0148225 A1.

[0008] A computer, or host, accessing a hard disk drive may use logical block addresses (LBAs) in commands to read and write sector data without regard for the actual locations of the physical sectors on the disc surfaces, i.e. by means of the hard disk controller the logical block addresses (LBAs) may be mapped to physical block addresses (PBAs) representing the physical location of the sector data. A large number of different mapping techniques for an indirect LBA-to-PBA read and write access are known in the prior art. In some embodiments LBA-to-PBA mapping does not change often. In other embodiments, especially in case of SMR, the LBA-to-PBA mapping may change with every write operation as the physical sectors are assigned dynamically.

[0009] Sector data read from a physical sector may be subjected to a forward error correction. For this purpose, additional error-correcting codes may be included in the data stored on the physical sector. The hard disk controller may monitor whether physical sectors are poorly legible, e.g. by means of the information derived from the forward error correction. If a physical sector is no longer legible, a CRC error may be reported.

[0010] A physical sector that is poorly legible or no longer legible is sometimes called a “bad sector” and will be referred to herein as unreliable or defective sector. Hard disk drives may autonomously “repair” defective sectors during regular operation by means of defect management. A defective sector may be replaced by a spare sector from a spare sector area which has been reserved for this purpose. The reference to the spare sector may be stored in a G-list (grown defects). This is called G-list remapping and may be logged by a monitoring system such as S.M.A.R.T. (Self-Monitoring, Analysis and Reporting Technology).

[0011] Moreover, when producing a hard disk drive, the manufacturer may recognize unreliable or defective sectors on the disk surfaces which can be mapped out by means of a P-list (primary defects) so that the hard disk drive skips these unreliable or defective sectors. This is called “sector skipping.”

[0012] In the cases of both G-list remapping (grown defects) and P-list remapping (primary defects), mapping out the defects may be achieved by changing the association between the logical block addresses (LBAs) and the physical block addresses (PBAs) of the affected physical sector. To the computer or host, the logical block still appears to be error-free. Remapped sector data may, nevertheless, affect the access time in some embodiments and, as soon as all spare sectors from the spare sector areas are in use, it is time to replace the hard disk drive.

[0013] The U.S. Pat. No. 7,408,731 B2, entitled “Track allocation method of disk drive,” describes a disk surface having at least two types of track widths, that is an area with overlapping tracks (“shingled tracks,” ST) and an area with conventional, non-overlapping tracks (“tiled tracks,” TT). Storage space which is missing due to a defective track is regained by adding additional overlapping and thus space-
saving tracks to the “shingled tracks” area (ST). Defective tracks are skipped while writing the bands and are not used for any advantageous purpose.

More specifically, the defective track 304 depicted in FIG. 3(b) of U.S. Pat. No. 7,408,731 B2 simply remains unused because the track above the defective track 304 is a wide track having the width of the write element thereby incorporating its own guard region. Furthermore, the band 310 is allocated in such a way that the defective track 304 is located at a position between the upper and lower boundary of the band 310, i.e., at a position in the middle of the band 310, which is a position without benefit. The U.S. Pat. No. 7,408,731 B2 does not suggest to shift the upper or lower boundary of the band 310 to the position of the defective track 304 in order to use the defective track 304 as a guard region.

In FIG. 6(b) and FIG. 9 of U.S. Pat. No. 7,408,731 B2 and in all corresponding and subsequent examples at least one conventional, non-overlapping track 305 (“tilted track,” TT) having the width of the write element is inserted between the lower end of the band 201 and the subsequent defective track 304 which makes it impossible to use the defective track 304 as a guard region. In concrete terms, the U.S. Pat. No. 7,408,731 B2 does not disclose a defective track which is used as a guard region and hence U.S. Pat. No. 7,408,731 B2 does not anticipate the invention hereinafter.

SUMMARY OF THE INVENTION

Aspects of the present disclosure are directed to the management of unreliable or defective sections on a data carrier surface, such as a defective track or one or more defective physical sectors. In accordance with the claims, a data carrier surface and/or a corresponding storage device are configured for overlapping data tracks. At least one guard region, guard track or guard segment is placed onto the physical location of an unreliable or defective section, to such an extent that the guard region, the guard track, or the guard segment completely or at least partially covers the unreliable or defective section.

In some embodiments, the replacement of an unreliable or defective sector may be attained by repositioning an existing guard region onto the physical position of the track (or tracks) affected by the unreliable or defective sector (or sectors) and by shifting the boundaries of the bands to the new position of the repositioned guard region. This may result in bands with a variable number of tracks, separated by the track (or tracks) affected by the unreliable or defective sector (or sectors), which now acts as a guard region.

In at least one embodiment, an additional guard region may be positioned on a defective track or on several adjacent defective tracks, i.e., tracks with unreliable or defective sectors. This may be done to reduce the write amplification. In other embodiments, guard regions may be placed onto tracks with elevated numbers of primary defects. This may be done during the production of the hard disk drive at the manufacturer.

The aforementioned and many further aspects, variants, objectives, and advantages of the invention will be comprehensible to those skilled in the art after reading detailed descriptions of the embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

Further features, advantages, and potential applications will be apparent from the drawings. All described and/or illustrated features, alone or in any combination, independent of the synopsis in individual claims, constitute the subject matter of the invention.

Detailed Description of the Invention

FIG. 1 shows an SMR hard disk drive 1 as an example of a storage device. The disks with a magnetic layer on the disk surfaces 2 spin around the rotational axis of the spindle 6, upon which the individual disks are mounted.
Tracks 3 on the disk surfaces 2 are divided into sections or segments, referred to herein as physical sectors 4 or sectors 4.

[0054] To perform read and write operations, the read/write heads 8 are shifted by an actuator arm to the desired track 3. The actuator arm is moved by an actuator 7, typically a voice coil motor (VCM). The actuator 7 is controlled by a hard disk controller 10. The hard disk controller 10 communicates with a host system 9 and has access to a memory 11. The memory 11 may, inter alia, contain a P-list and a G-list and may buffer sector data.

[0055] FIG. 2 shows a side view of a disk stack 13 (platters), which, in this example comprises three disks or six disk surfaces 2 since each disk, with upper and lower sides, has two magnetic layers. Cylinder 12 encompasses all concentric tracks 3 that are stop one another in the disk stack 13.

[0056] For shingled magnetic recording, the tracks 3 on the disk surfaces 2 are grouped in bands 18. This is demonstrated in FIG. 3, showing an enlarged sectional view of a band 18 comprising eight tracks 3. In the present disclosure, the tracks 3 are numbered according to the scheme n, n+1, n+2, etc., indicating that the tracks 3 and the bands 18 may be located at any suitable position on the disk surface 2.

[0057] In the example as per FIG. 3, the read/write head 8 comprises a write element 15, which is twice as wide as the read element 16. The arrow 19 indicates the relative direction of movement of the read/write head 8. The write element 15 writes overlapping data tracks 17, which are depicted with a pattern. For illustrative purposes, two different patterns are used to make the overlapping data tracks 17 more distinguishable. Moreover, in the drawings, the sectional view of the data tracks 17 are shown slightly offset along the writing direction 19 so that the overlapping structure is visible. Actual data tracks 17 continue in both directions along their respective tracks 3.

[0058] The numbering of #1 to #8 labeled on the data tracks 17 illustrates the order in which the overlapping data tracks 17 are to be written by the wide write element 15. By overlapping the data tracks 17, the effective track width 5 is halved in this case.

[0059] Individual bands 18 are separated by inter-band gaps, referred to herein as guard regions 14. FIG. 3 shows a guard region 14 on track n+8, marked with a dot pattern. In the illustrated configuration, the guard region 14 occupies one single track 3, referred to herein as a guard track 14. In other embodiments, depending on the width of the write element 15, the width of the guard region 14 may also be greater, for example, a multiple of the track width 5.

[0060] The guard track 14 is required to close off and delimit the band 18 so that the wide write element 15 does not overwrite any tracks 3 of a subsequent band 18. E.g., in order to write sector data onto track n+7, as shown, the wide write element 15 must be positioned on both, the track n+7 and the guard track 14 on track n+8.

[0061] As shown in FIG. 3, if sector data on the first track of the band 18 (track number n) is to be altered or rewritten, the data of all subsequent tracks 3 up until the guard track 14 must first be read out and buffered at a temporary location or in a memory 11, and must finally be rewritten, as the contents of each subsequent track 3 will be destroyed during the writing process. This is referred to as read-modify-write or write amplification.

[0062] FIG. 4 shows by way of example how track n+1 can be read out from a full band 18. The read/write head 8 is positioned so that the active read element 16 is located above track n+1. The relative direction of movement of the read/write head 8 is indicated by the arrow 19. The read element 16 matches the width of the tracks 3, i.e., the read element 16 is designed and optimized for the track width 5. This also applies to the effective width of the write element 15, designed to write data tracks 17, which are twice as wide as the track width 5 in this case.

[0063] The definition of the track width 5 in shingled magnetic recording as used in the present disclosure is based on the width of the remaining readable data track 17 after being overlapped with an adjacent data track 17. This remaining readable data track 17 constitutes the track 3 for which the read element 16 is designed or optimized.

[0064] Physical sectors 4 are sections of a track 3. The terms “sector” and “track” are therefore closely related technically and, depending on the desired embodiment, often equally applicable. Commonly, the umbrella term “track” is also representative of a portion of the track 3 under consideration. Whenever a track 3 is mentioned in the present disclosure, it can also refer to a physical sector 4 that is situated on it. Conversely, if a physical sector 4 is mentioned, the relevant operation may alternatively be applied to the entire track 3 or larger parts of the track 3.

[0065] The terms “track” (or “track number”) and “cylinder” (or “cylinder number”) are likewise closely related technically. Whenever a process is said to take place on a track 3, this may also concern the associated cylinder 12. Conversely, if a “cylinder” is mentioned, this may imply involvement of at least one of the tracks 3 on that cylinder 12.

[0066] If a track 3 or band 18 is referred to as “preceding,” “above,” “upwards,” or at an “upper” location, what is meant is that this track 3 or band 18 may be located further outside on the disk surface 2 and/or may have a smaller track or cylinder number. If a track 3 or band 18 is “successing,” “below,” “downwards,” or at a “lower” location, this track 3 or band 18 may be located further inside on the disk surface 2 and/or may have a greater track or cylinder number. Depending on the embodiment, a reverse orientation (e.g. further inside instead of further outside) or a numbering of the tracks and cylinders in the opposite direction may also apply.

[0067] In the present disclosure, the term “guard region” is used as an umbrella term for “guard track” and “guard segment.” A “guard track” is defined as a guard region consisting of one track. A “guard segment” is defined as a section of a guard region having a width of one or more tracks. As a general term, a “guard region” may consist of just one track or more than one track.

[0068] In the present disclosure, the term “defective sector” is used as an umbrella term for a section of a track 3 which is poorly legible, unreliable, or longer legible, or defective. Also, the term “defective section” is used as a generalized term for “defective sector.” Whenever a “defective sector” or a “defective section” is mentioned in the present disclosure, such defect may have any severity level. It is to be explicitly noted that the replacement of a defective section is possible regardless of said severity level. The same applies for the term “defective track.”

[0069] FIG. 5 through FIG. 10 show bands 18 of a first embodiment. A read/write head 8 is used, whose write element 15 is twice as wide as the read element 16. The bands 18 each comprise four tracks 3 in the initial state. However, any other desired number of tracks 3 per band 18 is possible. The number of four tracks 3 is chosen here as a means of better illustration.
[0070] The guard tracks 14 are located between the bands 18. In the illustrated examples, all bands 18 are fully occupied. Each track 3 is recorded with sector data, labeled with letters “A” to “L.” In the upper half of the 2nd band on track n+6, as per FIG. 5, a poorly legible section 20 is shown (“defective”), whose sector data is marked with the letter “F.” This defective section 20 is a grown defect which may have been detected during the regular operation of the hard disk drive 1.

[0071] If sector data is poorly legible, it is usually remapped, i.e., stored at another location. A reserve area or spare sector area may be provided for this purpose, and remapping may be done by means of logical block addressing (LBA). The hard disk controller 10 may hide the physical position of the defective section 20 by using a physical sector from the spare area sector instead. Also, the hard disk controller 10 may hide a defective track by using a spare track. This process is state of the art and is known as G-list remapping.

[0072] In the first embodiment and in further embodiments, small remaining spare sector areas are optional. Instead, according to one aspect of the invention, defective sections 20 are repurposed to guard regions 14. The portion of the disk surface 2, which is necessary for the guard regions 14, thus simultaneously functions as a spare sector area for defective sectors 20.

[0073] In order for a defective track 3 (with at least one defective sector 20) to be able to act as a guard region 14, the current guard region 14 may be displaced to the position of the defective track 3, and the boundaries of the corresponding bands 18 may be shifted to the level of this repositioned guard region 14. This may result in two bands 18 with a variable, i.e., different number of tracks 3, which are separated by the defective track 3 now acting as guard region 14.

[0074] Based on the initial state shown in FIG. 5, the 2nd band in FIG. 6 is “repaired” by repositioning a guard track 14 from track n+4 to track n+6, which is the track 3 with the defective sector data “F.” This track 14 is first read out and then, due to the twice-as-wide write element 15, written onto the tracks n+4 and n+5. Subsequently, the entire retrieveable sector data “F” on track n+6 (if possible, including the poorly legible section 20) is read out and, due to the twice-as-wide write element 15, written onto the tracks n+5 and n+6. The defective track n+6 now acts as a new guard track 14. Alternatively, instead of performing the read and write operations track by track, it is also possible to read out both tracks, n+5 and n+6, in a first step and to write the cached sector data of both tracks to their respective target tracks 3 in a second step. This variant is demonstrated in the flowchart as per FIG. 13 and is described further below. In both cases, the sequential order of the sector data “A” to “L” remains, as shown in FIG. 6, even after the reconfiguration.

[0076] Those skilled in the art will recognize that the sector data of bands 18 needs not be rewritten as part of the reconfiguration of band boundaries if the physical sectors 4 in the affected bands 18 are empty or in case the content of these physical sectors 4 has been released by the file system. In some cases the bands 18 need not to be completely empty, and rewriting sector data is still not necessary for the reconfiguration. For example, as per FIG. 5 and FIG. 6, if sector data “E” and “F” have been released by the file system, rewriting these sector data onto the tracks n+4 and n+5 is not necessary. These aspects also applies to further embodiments described below.

[0077] Depending on whether a defective sector 20 is located in the upper or lower half of the affected band 18, the upper or the lower boundary of the band 18 may be moved in order to reconfigure the bands 18. In the previous example as per FIG. 5 and FIG. 6 the defective sector 20 is located in the upper half of the band 18.

[0078] FIG. 7 shows an example, wherein the defective sector 20 is located in the lower half of the band 18, namely on track n+7 of the 2nd band. As a means of “repair,” the lower band boundary may be shifted.

[0079] Shifting the lower band boundary may be done by reading out all sector data that is affected by the shift, buffering this data at a temporary location, a cache or in the memory 11, and finally by rewriting the data, displaced by one track 3. In particular, as per example in FIG. 7 and FIG. 8, the sector data on all tracks 3 between track n+7 and track n+8 (both inclusive) are read and buffered in the memory 11. Subsequently, the sector data of track n+7 and track n+8 are rewritten, displaced by one track 3 downwards, onto the tracks n+8 and n+9, i.e., sector data “G” is shifted from track n+7 to track n+8, and sector data “F” is shifted from track n+8 to track n+9. In this embodiment, the data are displaced by one track 3, since the guard region 14 is one track wide. Lastly, due to the overlapping structure of the data tracks 17, the sector data originating from the tracks 3 of the 3rd band also have to be rewritten (track n+10 to track n+13), until the guard track 14 on track n+14 is reached. Sector data “I,” “J,” “K,” and “L” are therefore rewritten but do not shift position. As before, this process ensures that the sequential order of the sector data ("A" to "L") is preserved after the reconfiguration.

[0080] In the best case, no read-modify-write is required for the reconfiguration of occupied bands 18. This is illustrated by the next example: FIG. 9 shows defective sector data “H” on track n+8, and in accordance with FIG. 10, as a means of “repair,” the guard track 14 on track n+9 is moved to track n+8. The lower boundary of the 2nd band is shifted by one track upwards so that the 2nd band consists of three tracks 3 and the 3rd band consists of five tracks 3. The official location of sector data “H” is displaced from track n+8 to track n+9. Due to the wide write element 15, sector data “H” has already been written onto the former guard track 14 on track n+9 and hence, in this case, read and write operations are not necessary for reconfiguration.

[0081] The reconfigured arrangement of the bands 18, as illustrated in FIG. 6, FIG. 8, and FIG. 10 have no adverse effect on performance during read operations. This may distinguish the first embodiment (and further embodiments) from conventional solutions, which typically use a separate spare sector area. In particular, in the first embodiment (and in further embodiments) the sector data is still stored in the same order on the tracks 3 after the reconfiguration, and the read element 16 can continuously read large files or data from track to track without the need to spanning greater distances when seeking another track 3. Therefore, even if disk surfaces 2 are affected by newly recognized grown defects, i.e., defective sectors 20, the first embodiment (and further embodiments)
may have regular seek times corresponding to an error-free SMR hard disk drive without any grown defects.

Conventional hard disk drives may store a reference to a spare sector in a G-list (grown defects list). This spare sector, located in a spare sector area, may replace the defective sector 20, a process also referred to as remapping. In the first embodiment (and further embodiments), this approach is optional. Instead or additionally, information about the reconfiguration of the bands 18 may be stored in a new type or extended version of G-list, referred to herein as an “extended G-list.” To this end, it suffices to store the track numbers of the guard tracks 14 (located between the bands 18) in the extended G-list. The beginning of each band 18 may be determined by increasing the track number of the previous guard track 14 by one. The end of each band 18 may be determined by decreasing the track number of the subsequent guard track 14 by one.

FIG. 11 illustrates the process of updating the entries in an extended G-list to reconfigure the bands 18. Based on the example shown in FIG. 5, a part of an extended G-list (intended for band boundaries) is shown. In the initial state, the 1st, 2nd, and 3rd bands are assigned to the track numbers n+4, n+9, and n+14, each track number representing a guard track 14. After the reconfiguration as per FIG. 6, the entry of the 1st band changes from track n+4 to track n+6. FIG. 12 illustrates the process of reconfiguration based on the example shown in FIG. 9 and FIG. 10. Here, the entry of the 2nd band changes from track n+9 to track n+8.

In addition to the reconfiguration of band boundaries, in order to preserve the sequential order of the sector data (e.g., sector data “A” to “L” in FIG. 5 through FIG. 10), references to the new position of shifted sector data, now located on alternate tracks 3, may be stored in the extended G-list. Typically this is done by means of logical block addressing (LBA).

A host system 9, which accesses a hard disk drive 1, may use logical block addresses (LBAs) in commands to read and write sector data without regard for the actual locations of the physical sectors 4 on the disc surfaces 2. E.g., by means of the hard disk controller 10, LBAs may be mapped to physical block addresses (PBAs) representing the physical sectors 4. A large number of different mapping techniques for indirect LBA-to-PBA read and write access are known in the prior art.

In some embodiments, LBA-to-PBA mapping does not change often. With regard to the extended G-list remapping, as described above, the LBA-to-PBA association may only change in the case of a reconfiguration of band boundaries, that is, as soon as at least one guard region 14 shifts position. For example, if the host system 9 requests sector data “E,” the corresponding logical block addresses point to physical sectors 4 on track n+5 by means of logical block addressing. After the reconfiguration, as per FIG. 6, said logical block addresses, in accordance to entries in the extended G-list, now point to physical sectors 4 on track n+4, which, in this case, has previously been used as a guard track 14.

In other embodiments, the LBA-to-PBA mapping may change with every write operation as the physical sectors 4 are assigned dynamically. Such embodiments may not use a G-list or an extended G-list but instead may store the LBA-to-PBA association and the configuration of the bands 18 in a map or another type of data structure.

For instance, U.S. Pat. No. 8,756,399 B2, entitled “Mutable association of a set of logical block addresses to a band of physical storage blocks,” describes such a dynamic association, the disclosure of which is hereby incorporated by reference in its entirety. U.S. Pat. No. 8,756,399 B2 suggests a map format which, among other things, stores “LBA sets mapped to bands” and “LBAs allocated to existing sectors.” Those skilled in the art will recognize that such a map format or a comparable approach could be extended or modified to store positions of displaced guard regions 14. Also, those skilled in the art will recognize that, as soon as a band 18 must be reconfigured due to a recognized grown defect (defective sector 20), the necessary remapping of logical block addresses (LBAs) to physical sector 4 may be achieved by updating said map.

It is to be explicitly noted that the present invention can be implemented using any type of remapping technique, including, but not limited to, logical block addressing (LBA) and dynamic or mutable association of logical block addresses to physical sectors 4. Also, those skilled in the art will understand that the method by which information about displaced guard regions 14, band boundaries, and sector data is stored and maintained depends on the remapping technique used for a specific embodiment, and that this information must not necessarily be stored in an extended G-list.

FIG. 13 shows the flowchart to the first embodiment. Variable “d” defines the track number of a track 3 with a defective sector 20, typically a grown defect. Track number “a” defines the location of the upper guard track 14, which is adjacent to the upper boundary of the affected band 18, and track number “b” defines the location of the lower guard track 14, which is adjacent to the lower boundary of the band 18.

First, in step 21, it is determined whether the defective sector 20 is located in the upper or in the lower half of the affected band 18.

$$d = \frac{a + b}{2}$$

If the inequality proves true, the defective sector 20 is allotted to the upper half of the band 18 and, in step 22, all sector data on the tracks 3 are read and cached in memory 11, which essentially are located between the upper guard track 14 and the track 3 with the defective sector 20, that is, all tracks 3 below track number “a” through and including track number “d”.

In step 23, the upper guard track “a” is displaced to track number “d”:

$$a \rightarrow d$$

This is done by changing the corresponding entry in the extended G-list, thereby shifting the boundaries of the adjacent bands 18 as described with respect to FIG. 11 and FIG. 12.

Finally, in step 24, the cached sector data is written back onto the tracks 3, displaced upwards by one track.

$$c_{new} = c_{old} - 1$$

where “c” are track numbers of physical sectors 4 indicating the original location (“old”) and the target position (“new”) of sector data.

Returning to step 21, if the defective sector 20 is located in the lower half of the affected band 18, in step 25, all sector data, starting with track number “d” up until the end of the succeeding band 18, is read and cached in memory 11.
Reconfiguration of the bands 18 takes place in step 26. First, the former track number of the lower guard track “b” is stored temporarily as variable “b_temp”.

Next, the lower guard track “b” is moved to track number “d” by changing the corresponding entry in the extended G-list.

Finally, in step 27, the cached sector data is written back onto the tracks 3, displaced downwards by one track, up to (and including) the former track number of the lower guard band “b_temp’’.

where “c” is the track numbers of physical sectors 4 indicating the original location (“old”) and the target position (“new”) of sector data.

The remaining cached sector data from the tracks 3 below track number “b_temp’’ is rewritten on the respective original tracks, i.e., back to the original location, until the next guard track 14 is reached. This is done, because the write element 15 writes overlapping data tracks 17.

For the upper boundary of the 2nd band, the retrievable sector data “G” on track n+7 is read (if possible including the poorly legible section). buffered, and rewritten onto the tracks n+6 and n+7 by means of the wide write element 15, whereby the defective track n+7 serves as a new guard track 14.

For the lower boundary of the 2nd band, the sector data of all tracks 3 from (and including) track n+10 to (and including) track n+19 are read and buffered in the memory 11. Subsequently, the sector data originating from the tracks n+10 through n+12 is rewritten onto the tracks n+11 through n+13, displaced downwards by one track. Sector data “J,” shown in FIG. 14 and FIG. 15, is thus displaced from track n+10 to track n+11. Sector data “K” is displaced from track n+11 to track n+12, and sector data “L” from track n+12 to track n+13. Finally, due to the overlapping structure of the data tracks 17, the remaining sector data from the tracks 3 of the 3rd band (track n+14 through track n+19) is rewritten to its original location until the guard track 14 on track n+20 is reached. Sector data “M,” “N,” “O,” “P,” “Q,” and “R” are thus rewritten, but do not shift position. The sequential order (“A” to “X”) is preserved after the reconfiguration.

After the reconfiguration, the 3rd band consists of nine tracks 3 and is noticeably wider, as shown in FIG. 15. Therefore, optionally, a redistribution of the tracks 3 to adjacent bands 18 may be carried out, to avoid the write amplification being excessively large when updating the sector data in the 3rd band, e.g., due to a random write access. This is illustrated in FIG. 16. The guard track 14 between the 3rd band and the 4th band has been displaced upwards from track n+20 to track n+18 by two tracks. The reconfiguration is carried out by reading, buffering, and rewriting sector data in the same manner as described for the lower boundary of the 2nd band with respect to FIG. 15.

As a result of the reconfiguration, the 3rd band consists of seven tracks 3, as depicted in FIG. 16, and since the 3rd band now has only one additional track 3 compared to the initial state, the additional write amplification in the case of a random write access is insignificant. The 4th band now comprises eight tracks 3, that is two additional tracks 3 compared to the initial state. In order to achieve an optimal distribution of the additional tracks 3 here as well, the guard track 14 at the lower boundary of the 4th band may optionally be displaced from track n+27 to track n+26, causing the 4th band to be one track narrower while a 5th band gets one track wider. (Not shown in the drawings.) This additional, yet optional, optimization results in the 1st, 3rd, 4th and 5th bands having adopted an additional track 3, thereby compensating for the 2nd band, whose width has been reduced to two tracks 3 due to the defective sectors 20.

FIG. 17 shows a situation where defective sectors 20 are located on two directly adjacent tracks 3, namely the tracks n+17 and n+18, which are both located in the 3rd band. “Repair” is nonetheless possible, as illustrated in FIG. 18. The guard track 14 between the 2nd and 3rd bands is shifted from track n+13 to track n+17, and the guard track 14 between the 3rd and 4th band is shifted from track n+20 to track n+18 by changing the corresponding entries in the extended G-list. The 3rd band is, in effect, completely canceled, i.e., since the shifted guard tracks 14 now are located next to each other, the 3rd band contains zero tracks. In the present embodiment, the original numbering of the bands 18 is nevertheless main-
tain. In other embodiments, the bands 18 may be renumbered, so that by way of example, the 4th band is assigned the number of the 3rd band.

[0109] Furthermore, the example in FIG. 18 reveals, how the former sector data of the canceled 3rd band is distributed evenly onto the 1st, 2nd, and 4th bands, so that each of these bands 18 incorporates two additional tracks 3, resulting in eight tracks 3 per band 18. This is done by shifting the guard track 14 between the 1st and 2nd band from track n+6 to track n+8. The approach corresponds to the description in regard to FIG. 16.

[0110] The rearrangement of the sector data from the initial state shown in FIG. 17 to the new configuration shown in FIG. 18 can be comprehended by means of the letters “A” to “X,” which are labeled on the data tracks 17 for this purpose. Reconfiguration may be done by reading, buffering, and rewriting sector data and may be carried out in the manner described above.

[0111] Additional defective sectors 20 on a further track 3 in the same band 18, e.g., the 3rd band in FIG. 17 may be compensated by involving another adjacent band 18, that is, by involving an adjacent band 18 per defective track 3. For instance, with reference to FIG. 18, in the case where a further defective sector 20 were located on track n+16, an additional “spare track” could be made available by using the guard track 14 on track n+8. (Not shown in the drawings.)

[0112] FIG. 19 and FIG. 20 demonstrate a case in which, by way of example, three tracks 3 in one band 18 contain defective sectors 20. For illustrative reasons, the bands 18 in this example each comprise four tracks 3 in the initial state, as per FIG. 19. The three defective tracks 3 are located in the 5th band on the tracks n+20, n+22, and n+23, making the 5th band largely unusable. Referring to FIG. 20, “repair” is made by displacing the guard tracks 14 from the tracks n+14, n+19, and n+24 to the tracks n+20, n+22, and n+23, that is, by displacing the guard tracks 14 to the 3 tracks containing defective sectors 20.

[0113] Additionally, to prevent the 3rd band from becoming undesirably wide, the guard track 14 on track n+9 may be displaced to track n+13, and the guard track 14 on track n+4 may be displaced to track n+6, as shown in FIG. 20. The resulting bands 18 thus maintain a balanced number of tracks 3. The 1st, 2nd, and 3rd band each adopts two additional tracks 3. Due to the defects, the 4th band merely includes one single track 3 and the 5th band formally has zero tracks and may be canceled. The 6th band now consists of five tracks 3.

[0114] In some embodiments, such as the first and second embodiment, the sequential order of all sector data is preserved by repositioning the sector data on all tracks 3 affected by the reconfiguration of band boundaries, i.e., the displacement of a guard region 14. This may be done to optimize sequential read and sequential write speeds. However, alternatively, when shifting a guard track 14, it is sufficient to reposition the sector data of a single track 3. Basically, the guard track 14 swaps position with the sector data of the defective track 3. All other sector data remains in its old position. The sequential order of sector data on adjacent tracks 3 is not necessarily preserved. This approach may minimize the amount of data that must be read, buffered, and rewritten to reconfigure the bands 18.

[0115] FIG. 21 and FIG. 22 provide an example: A defective sector 20 is located on track n+2, as illustrated in FIG. 21, and as a means of “repair,” the guard track 14 on track n+4 is moved to track n+2, as illustrated in FIG. 22. In turn, sector data “C” originating from the defective track 3 attains the former position of the displaced guard track 14, and is thus moved from track n+2 to track n+4 by means of a read and write operation.

[0116] After the reconfiguration as per FIG. 22, the resulting bands 18 have a width of two tracks 3 (1st band) and six tracks 3 (2nd band). During the reconfiguration, sector data “D” is not shifted (such as in the first and second embodiments), and therefore the resulting order of sector data is non-sequential, i.e. “A,” “B,” “D,” “C,” “E,” (etc.).

[0117] Those skilled in the art will recognize that, depending on the objective, an appropriate variant should be selected that is advantageous in regard to criteria such as seek time, sequential read/write speed, or write amplification. The selected variant may involve a sequential or a non-sequential arrangement of sector data on adjacent tracks 3 or a combination of both.

[0118] Alternatively or additionally, the order of sector data may be managed dynamically, e.g., depending on available free sectors in the affected bands 18. Also, depending on the workload of the SMR hard disk drive 1, reorganizing the order of sector data may be done at a later point in time after the reconfiguration of the bands 18, e.g. as part of a “scrubbing operation” (garbage collection) during idle time, as described in the aforementioned U.S. Pat. No. 8,756,399 B2.

[0119] Various embodiments of the present invention may be implemented regardless of the direction, orientation, and structure of the overlapping data tracks 17 and bands 18. For example, the overlapping data tracks 17 may be written from the outer diameter to the inner diameter of the disk surface 2, or from the inner diameter to the outer diameter.

[0120] Moreover, it is possible to combine both radial directions on the same disk surface 2, as is described in the U.S. Pat. No. 8,699,185 B1, entitled “Disk drive defining guard bands to support zone sequentiality when butterfly writing shuffled data tracks,” the disclosure of which is hereby incorporated by reference in its entirety. E.g., a first zone (or band 18) may be written while seeking from track to track in a first radial direction resulting in data tracks 17 overlapping in this first radial direction and a second zone (or band 18) may be written while seeking from track to track in the opposite radial direction resulting in data tracks 17 overlapping in the opposite direction.

[0121] Furthermore, a band 18 may comprise data tracks 17 with overlaps in both radial directions. The overlapping data tracks 17 may diverge in the middle of the band 18 (or at a location near the middle), e.g. track n+2 and track n+3 of the 1st band, as illustrated in FIG. 23. This type of band 18 is referred to herein as a “symmetrical band.” Adjacent symmetrical bands 18 share a common guard region 14. For instance, the 1st and 2nd symmetrical bands as per FIG. 23 share a guard track 14 on track n+5, which is used by the wide write element 15 from both sides. Symmetrical bands 18 may be useful to reduce the write amplification, since the number of tracks 3 which must be updated via read-modify-write is halved.

[0122] The symmetrical bands 18, illustrated in FIG. 23, each comprise four tracks 3 in the initial state. At least one defective sector 20 is located on track n+7 in the 2nd band which, by way of example, is “repaired” by displacing a guard track 14 from track n+5 to track n+7, as shown in FIG. 24. The width of the 1st band thus increases from four to six tracks (track n+1 to track n+6), and the width of the 2nd band is
reduced from four to two tracks (track \(n+8\) and track \(n+9\)). The boundaries of the 1st and 2nd band are shifted accordingly.

[0123] In order to preserve the fully symmetric structure of the overlapping data tracks 17 within the bands 18 even after changing the width of the bands 18, the line of symmetry of each affected band 18 may be shifted. For example, as seen in Fig. 24, the overlapping data tracks 17 now diverge between track \(n+3\) and track \(n+4\) in the 1st band and between track \(n+8\) and track \(n+9\) in the 2nd band. The reconfiguration is achieved by reading, buffering, and rewriting the sector data of the corresponding tracks 3. Despite the fully occupied symmetrical bands 18 all sector data is still accommodated, even after the reconfiguration.

[0124] Further variations and embodiments are possible. For instance, instead of writing diverging data tracks 17 from the center line toward the outer band boundaries, the overlapping data tracks 17 may be written from the outer band boundaries toward a guard region 14 located in the middle (or near the middle) of the symmetrical band 18. Even in this case, it is possible to "repair" a defective sector 20 within the band 18 by placing the guard region 14 onto the track 3 with the defective sector 20, which is not necessarily a track 3 in the middle of the band 18. The entire sector data of the affected band 18 can be accommodated by adjusting the order and/or the overlap of the data tracks 17 within the band 18.

[0125] In some embodiments, disclosed above, if a defective sector 20 is found, the upper and/or lower boundaries of the affected band 18 are adjusted, which, in particular, occurs for the entire length of the tracks 3, that is, when displacing a track 3 or guard track 14, this is done for all sectors 4 of the track 3 or guard track 14. In the subsequent third embodiment as per Fig. 25 and Fig. 26, however, only individual sections of the tracks 3, typically sectors 4, are displaced to alternate tracks 3.

[0126] In the example as per Fig. 25, the bands 18 have a width of four tracks 3 in the initial state, however, any other desired width is possible. Furthermore, Fig. 25 shows physical sectors 4, depicted as sections, on concentric tracks numbered \(n\) through \(n+9\). Defective sectors 20, represented by a solid black ellipse, are located on track \(n+2\) (left of center), track \(n+5\) (right of center), and track \(n+8\) (left of center).

[0127] As a means of "repair," as shown in Fig. 26, it is not the entire guard track 14 which is displaced, but rather at least one sector 4 that acts as a distancing gap segment, i.e., a segment of a guard track 14, hereinafter referred to as "guard segment" 14. Moreover, the boundaries of the bands 18 are individually shifted per circle sector.

[0128] Concerning the defective sector 20 on track \(n+2\), according to Fig. 25, the closest guard segment 14 is located on track \(n+4\). This is the lower boundary of the 1st band. As shown in Fig. 26, only a guard segment 14 is shifted from track \(n+4\) to track \(n+2\), whereby the action is limited to a single circle sector. The remaining guard track 14 in the other circle sectors remains in its old position on track \(n+4\). A further defective sector 20 is located on track \(n+5\). Accordingly, in Fig. 26, the corresponding guard segment 14 is displaced from track \(n+4\) to track \(n+5\), thus onto the defective sector 20. The same procedure occurs with the defective sector 20 on track \(n+8\). The adjacent guard segment 14 on track \(n+9\) is displaced onto the defective sector 20 on track \(n+8\).

[0129] In the third embodiment, the bands 18 or, more specifically, the displaced sectors 4 and guard segments 14, may likewise be maintained in an extended G-list, which is however done separately for each circle sector on the disk surface 2. Also, in the third embodiment, a guard segment 14 may swap position with the sector data of a defective sector 20, while all other sector data remains in its old position, that is, the sequential order of the sector data is not preserved. This corresponds to the example illustrated in Fig. 21 and Fig. 22. However, depending on whether the preservation of the sequential order of sector data is beneficial for access times and/or desirable for some other reason, those skilled in the art will decide on an appropriate variant.

[0130] In several aforementioned embodiments, the location of a former guard region 14 is used as a replacement for storing user data, in particular, to accommodate the data located on a defective sector 20, or to accommodate the data located on an entire track 3 (or several tracks 3) having at least one defective sector 20.

[0131] However, in a fourth embodiment, the sector data located on a newly discovered defective sector 20 (grown defect), or the sector data located on an entire track 3 affected by such a defective sector 20 is stored in a spare sector area in a conventional manner. The defective sector 20 or the entire track 3, on which at least one defective sector 20 is located, is instead used as an additional guard segment or guard track 14.

[0132] By dividing the affected band 18 and by introducing an additional guard segment or guard track 14 on the track 3 with the defective sector 20, two "sub-bands" with a reduced number of tracks 3 are created. The lower track count per "sub-band" may reduce the write amplification e.g., in the case of random write access.

[0133] The hard disk geometry and structure, i.e., the division of the hard disk 1 into zones 28, bands 18, tracks 3, physical sectors 4 as well as cylinders 12 and read/write heads 8, may be defined and stored as part of the firmware data of the hard disk controller 10. Fig. 27 shows, by way of example, the innermost zone 28 on a disk surface 2 and a conventional, evenly spaced arrangement of guard tracks 14. The innermost zone 28 comprises tracks 3, numbered from \(n\) to \(n+14\). Track numbers smaller than \(n\) are thus representative of the tracks 3 of the outer zones 28 that are not shown in the drawings.

[0134] For illustrative purposes, a low number of tracks 3 is chosen in the drawings which should not be construed as limiting the scope of the embodiments. As shown in Fig. 27, the innermost zone 28 is divided into three bands 18, wherein each band 18 consists of four tracks 3 and is separated by a guard track 14. Such an arrangement may be defined and stored in the firmware of the hard disk controller 10 or may be stored in a special firmware data section on a disk surface 2.

[0135] When producing a hard disk drive 1, there are typically defective sectors 20 on the new disk surfaces 2 which are recognized as potentially defective sectors 20 during the production process (e.g., servowriter, "low-level format," test-phase, etc.) and which are known as "primary defects." These defective sectors 20 may be skipped by means of a technique known as "sector slipping." Since the hard disk drive 1 is still empty at this stage, a defective sector 20 can be modified by assigning the logical block address of the defective sector 20 to the next physical sector 4 and shifting the addresses of all subsequent sectors 4 by one. The sequential order of the sector data on the tracks 3 is preserved. The assignment of logical block addresses to physical sectors 4 ("logical block addressing," LBA) may be stored in a so-called P-list (primary defects) as part of the firmware data. In order to skip primary defects in the manner described, spare
areas must be reserved on the disk surfaces 2 of the hard disk drive 1 to compensate for the “lost” defective sectors 20. This approach is state of the art.

[0136] FIG. 28 and FIG. 29 show a fifth embodiment. Defective sectors 20 are located on the innermost zone 28 of a disk surface 2. The innermost zone 28 corresponds to the zone 28 depicted in FIG. 27. The defective sectors 20, as per FIG. 28, are illustrated as solid black ellipses and may have been identified during the production of the hard disk drive 1. For instance, track n+1 contains four defective sectors 20, whereas track n is error-free. For illustrative reasons, it is assumed in the following that there are no defective sectors 20 in the areas cut-off at the right and left of the drawings.

[0137] In a conventional arrangement as per FIG. 27, a guard track 14 may be placed on every fifth track 3 in compliance with the specification that the bands 18 are four tracks 3 wide. The positions of defective sectors 20 are not taken into account.

[0138] To the contrary, in accordance with one aspect of the invention, in the fifth embodiment as per FIG. 29, the width of each band 18 is varied in such a way that the guard regions 14 are located, as often as possible, on tracks 3 with an increased number of defective sectors 20. Limits may be defined as to the minimum and maximum permissible number of tracks 3 in a band 18. In the illustrated example, while the target value could be four tracks 3 per band 18, the minimum permissible width of a band 18 could be three tracks 3, and the maximum could be five tracks 3.

[0139] As illustrated in FIG. 28, there are no defective sectors 20 on track n+9, which was originally intended for the guard track 14 as per FIG. 27, but there are a total of seven defective sectors 20 on track n+10. Therefore, as shown in FIG. 29, it is advisable to use track n+10 as a guard track 14 because the defective sectors 20 on track n+10 have no relevant disadvantages for a guard track 14. As a result, the 3rd band now consists of merely three tracks 3. Since the defective sectors 20 are now located on a guard track 14, there is no need to re-map these defective sectors 20 to a spare area. The size of spare areas on the disk surfaces 2 can be reduced; the total capacity of the SMR hard disk drive 1 increases. However, if the originally intended track n+9 were to be used for the guard track 14, the defective sectors 20 would be reflected as a loss in capacity.

[0140] Defective sectors 20, which cannot be covered by a guard region 14 due to their position, or due to limits such as the minimum and maximum permissible number of tracks per band 18, may be skipped by means of “sector skipping” in a conventional manner. Both the optimized positions of guard regions 14, as well as the defective sectors 20 skipped over by means of “sector skipping,” can be stored in an extended P-list.

[0141] The flowchart of FIG. 30 shows a simple heuristic method for finding advantageous tracks 3 for the guard regions 14 in the production of SMR hard disk drives 1. The starting point may be a test or scan of all physical sectors 4 on the hard disk drive 1 by which all defective sectors 20 are detected.

[0142] The final result of the optimization procedure, that is, the optimized positions of the guard regions 14, may be stored in an extended P-list (primary defects) analogously to the procedure according to FIG. 11 and FIG. 12. The extended P-list may contain the track numbers of all guard regions 14. The new, optimized position and width of the corresponding bands 18 may then be obtained indirectly from the stored positions of the guard regions 14.

[0143] The optimization procedure depicted in FIG. 30 may be performed separately for each zone 28 of each disk surface 2. First, in step 29, the error count per track 3 is determined by counting the defective sectors 20 of each track 3. Next, in step 30, the error count per track 3 is sorted by size for all tracks 3 in a zone 28 so that the track 3 with the most defective sectors 20 ranks first in a ranking list.

[0144] On the innermost track 3 of the zone 28 (or outermost track 3 of the zone 28, depending on the direction of SMR overlaps), a finishing guard track 14 is positioned by entering the corresponding track number into the extended P-list. This is done in step 31 of the flowchart. The innermost (or outermost) track 3 is typically the track 3 with the largest (or smallest) track number within the zone 28, and is located at the zone boundary.

[0145] In step 32, the track 3 with the highest error count (first entry) is taken from the ranking list and is removed from the ranking. Each track 3 taken from the ranking list is a candidate for the position of another guard track 14. The corresponding track number of such a track 3 may then be stored in the extended P-list as an optimized location for a guard track 14.

[0146] In step 33, it is checked, whether there is already an entry in the extended P-list referencing a guard track 14 located at a distance of less than the minimum permissible width of the bands 18, i.e., starting from the candidate’s track number, it is checked for both sides whether a guard track 14 on an adjacent or local track 3 has already been entered into the extended P-list or whether the candidate is located too close to the outer (or inner) zone boundary. If minimum spacing to adjacent guard tracks 14 and boundaries is ensured, the track number of the candidate is entered into the extended P-list as a new guard track 14; otherwise, the candidate is discarded.

[0147] Steps 32 and 33 are repeated until the ranking list is empty. This is controlled by means of the conditional construct in step 34. The lower entries in the ranking list typically have an error count of zero. These entries fill in the spaces between already placed guard tracks 14 in the further course of the process, always in accordance with the minimum distance to the nearest guard track 14 or band boundary. The steps of the flowchart can be comprehended in more detail by means of the example shown in FIG. 28 and FIG. 29.

[0148] Optionally, the process described above could be further optimized. E.g., instead of using the lower entries from the ranking list (with an error count of zero) to fill in the spaces between already placed guard tracks 14, these error-free entries may be skipped or deleted from the ranking list. Instead, in a final step, the remaining spaces between already placed guard tracks 14 (having an error count greater than zero) can be filled with evenly distributed guard tracks 14 by ensuring that the width of the corresponding bands 18 is close to the target value.

[0149] The optimization of the location and distribution of guard tracks 14, as described above, is performed separately per zone 28. This ensures that each track 3 within a zone 28 owns the same number of physical sectors 4, thereby allowing the direct comparison of the number of defective sectors 20 per track 3. Otherwise, if the number of physical sectors 4 per track 3 varies in the considered region, the number of defective sectors 20 per track 3 must be put in relation to the number of physical sectors 4 per track 3.
As an alternative to the basic optimization process shown in FIG. 30, a variety of known methods for solving the optimization problem can be used, in particular, approximation algorithms and heuristics from the fields of mathematical optimization, algorithmic discrete mathematics, and integer programming. Optionally, the constraints pertaining to the objective function of the optimization algorithm may be weighted differently, such as the minimum and maximum numbers of tracks 3 per band 18 and the uniform distribution of guard regions 14.

Another criterion that may be incorporated into the optimization process is the quality level of tracks 3 and/or the severity level of defective sections 20. In particular, the optimization algorithm may distinguish between unreliable sectors 20 and defective sectors 20. Furthermore, an assessment of how critical the situation is to be interpreted in adjacent physical sectors 4 of the same track 3 and/or on adjacent tracks 3 can help to make an optimal decision, as to on which track or tracks 3 a guard track or guard region 14 should be positioned. E.g., supposing a track 3 is affected by a defective sector 20 and in case adjacent physical sectors 4 on the same track 3 are of marginal reliability, this suggests to select this track 3 for a guard track 14.

Also, rather than counting the number of defective sectors 20 per track 3 the optimization algorithm may consider the length or percentage of defective sections 20 on the tracks 3. The length of defective sections 20 may be rated or weighted by severity level.

The application of the optimization process pursuant to FIG. 29 and FIG. 30 is not limited to the production stage of an SMR hard disk drive 1. Optionally, the end user can be provided with an optimization tool, e.g., as a software application. Software tools for reinitializing a hard disk drive are known and are state of the art, e.g., zero-fill diagnostic utilities, "low-level format," and "mid-level format," with which defective sectors 20 can be detected and "fixed." As part of such a surface diagnosis and reformattting, the software tool can also perform an optimization on the position and/or distribution of the guard regions 14, as described above. The end user, therefore, has the option to restore an SMR hard disk drive 1, which has been operated for a long time, back to a clean and well-performing state.

Concerning the aforementioned embodiments, a read/write head 8 is used having a write element 15 twice as wide as the read element 16. However, other embodiments may have a different ratio in regard to the width of the read- and write element 15, 16. Generally speaking, the track width of the write element 15 can be any value greater than the track width 5 of the read element 16.

By way of example, in a sixth embodiment pursuant to FIG. 31 and FIG. 32, the track width of the write element 15 is three times the track width 5 of the read element 16. The two bands 18 depicted in FIG. 31 each have five tracks 3. The guard region 14 consists of two adjacent tracks 3, being twice as wide compared to aforementioned embodiments. This is essential to prevent the write element 15 (now three times as wide) from writing onto the first track 3 of the next band 18.

As shown in FIG. 31, defective sectors 20 are located in the 2nd band on each of the tracks n+7 and n+8, thus two errors on two adjacent tracks 3. Because the guard region 14 in this embodiment consists of two adjacent tracks 3, it is still sufficient, to shift only one band boundary. This distinguishes the sixth embodiment from those aforementioned.

FIG. 32 illustrates, by way of example, how merely the upper band boundary of the affected 2nd band is shifted to “repair” the band 18. For this purpose, the guard region 14, consisting of two tracks 3, is displaced from the pair of tracks n+5 and n+6 to the pair of tracks n+7 and n+8, such that the guard region 14 covers both defective sectors 20.

Optionally, a uniform distribution of the number of tracks 3 per band 18 may be applied analogous to the example shown in FIG. 16. This has been omitted in FIG. 32 due to space demands and should not be construed as limiting the scope of the embodiment.

A guard region 14 consisting of two tracks 3, as illustrated in FIG. 31 and FIG. 32, may also be applied in a similar manner with all other embodiments presented, as well as with further embodiments. This may be done whenever the track width of the write element 15 is three times as wide as the track width 5 of the read element 16. Also, a guard region 14 may consist of more than two tracks 3 and/or the width of the write element 15 may be even wider.

It is to be explicitly noted that the guard regions 14 in the fifth embodiment pursuant to FIG. 29 may also comprise more than one track 3, and the write element 15 may have any suitable width. The aforementioned optimization algorithm may, in this case, consider the total number of defective sectors 20 of all tracks 3 covered by the width of the guard region 14. Also, the optimization algorithm may consider the size or percentage of defective disk surface 2, in terms of the square measure, that can be covered by the guard region 14. In general, the size, the width, or the severity level of a primary defect may be taken into account.

Furthermore, as mentioned above, the quality level of physical sectors 4 on adjacent tracks 3 may be taken into account while performing the optimization. E.g., supposing there is a defective sector 20 on a track 3 with the track number n, no defects on the upper adjacent track n−1, and a physical sector 4 of marginal quality on the lower adjacent track n+1, then it would be advantageous to position a guard region 14, consisting of two tracks 3, on the pair of tracks n and n+1 in order to use the opportunity to also exclude the physical sector 4 of marginal quality on track n+1. (Not shown in the drawings.) This optimization is possible without losing storage capacity.

Pursuant to some disclosed embodiments, the width of a guard region 14 is equal to the track width 5 or a multiple of the track width 5. Therefore, a guard region 14 may fit precisely into the grid of tracks 3. However, in other embodiments, guard regions 14 may also be implemented with a different width, which is specifically not a multiple of the track width 5, but, by way of example, is 1.5 times or 2.5 times the width of a track 3. It is to be explicitly noted that the present disclosure is not limited to guard regions 14 consisting of one or two tracks 3, as depicted in the drawings. A guard regions 14 may have any suitable width. Also, the width of a guard region 14 may be increased to enhance the reliability of stored data.

Optionally, the width of guard regions 14 may be varied individually or dynamically to take account of the severity level of defects, such as the size or width of defective sections 20 and/or the number of defective sectors 20 on a track 3. E.g., in the fifth embodiment, as part of the optimization process, the width of each guard region 14 may be adjusted individually, to optimally cover primary defects. The resulting width of the guard region 14 after the optimization may be any size and need not be a multiple of the track width.
In this case, the subsequent tracks may be shifted corresponding to the optimized width of the preceding guard region. Such a procedure of shifting tracks may be applicable, e.g., as part of a “low-level format,” since the hard disk drive does not contain any user data at the time of production.

Typically, a SMR hard disk drive comprises several disk surfaces mounted on top of one another in a disk stack. In the aforementioned embodiments, only guard regions and band boundaries of a disk surface affected by a defective section are reconfigured. This means that each disk surface may use individually positioned guard regions and bands, which are adjusted to local conditions (such as defective sectors) and which may vary from disk surface to disk surface in the disk stack.

Alternatively, all aforementioned embodiments and further embodiments may be implemented in such a way that the reconfiguration of the position of guard regions and band boundaries is done uniformly in the entire disk stack on all disk surfaces (or at least on more than one disk surface). E.g., with respect to the first, second, and third embodiments, as soon as a defective sector is detected on one of these disk surfaces, the corresponding guard regions and band boundaries shift position in the entire disk stack on all disk surfaces. After the reconfiguration, all corresponding guard regions in the disk stack are located above one another throughout the entire stack.

The reconfigured guard regions and/or bands may be maintained in an extended G-list analogously to the procedure in the previous embodiments. Yet, in this case, the extended G-list stores cylinder numbers (instead of track numbers), which may constitute obligatory locations for guard regions and band boundaries on more than one disk surface.

Also, those skilled in the art will recognize that, in the fifth embodiment pursuant to FIG. 29, optimizing the distribution of guard regions need not necessarily be done separately per disk surface. The position of guard regions can also be varied in such a way that they are located, as often as possible, on a cylinder (or several adjacent cylinders) depending on the width of the guard region, whose total number of defective sectors is significantly increased throughout the entire disk stack.

In such an embodiment, the track numbers n through n+14 as per FIG. 28 and FIG. 29 may be interpreted as cylinder numbers n through n+14, and the solid block ellipses may represent the defective sectors from the entire disk stack. That is, in the illustrations, every defective sector from any disk surface is indicated on a per cylinder basis, regardless of the specific disk surface from where the error is derived. For example, in such an embodiment, cylinder n is entirely error-free and cylinder n+1 contains four defective sectors as the sum from all disk surfaces.

Finally, for such an embodiment, the flowchart depicted in FIG. 30 may be modified to find cylinder numbers that are favorable for guard regions. By way of example, an error count per cylinder may be determined by counting the defective sectors on all tracks of the same cylinder in the entire disk stack. The error count per cylinder may be sorted by size for all cylinders in a zone. The guard tracks may be positioned on each disk surface of the disk stack by entering the corresponding cylinder number into a joint P-list.

It is to be explicitly noted that all examples shown in the drawings can, in a similar manner, also be carried out with any other embodiment, as well as with further embodiments. Therefore, the examples are universally applicable. Shifting band boundaries, the displacement of guard regions, guard tracks, and/or guard segments, as well as the rearrangement of sector data are possible, regardless of whether the underlying organization of the bands is implemented per cylinder sector, per disk surface, or by using an entire disk stack.

The present invention may, inter alia, be used during the production of a hard disk drive to map out primary defects or during regular operation of the hard disk drive to “repair” grown defects. Alternatively, the present invention may be used for both during the production as well as during regular operation. In this case, when optimizing the locations of the guard regions during the production by placing them onto tracks with an elevated number of primary defects, the manufacturer may mark off each guard region which includes such primary defects. E.g., guard regions which include at least one primary defect may be listed in a suitable table, such as an extended P-list and/or marked with a flag. This is done to indicate that a marked guard region should not be used for the replacement of grown defects during the regular operation of the hard disk drive. Instead, another non-marked guard region from the vicinity may be used to replace a new grown defect (such as a newly discovered defective sector).

As an alternative, a band having defective sectors on more than one track as described with reference to FIG. 14 through FIG. 20.

With regard to FIG. 14 through FIG. 20 as well as FIG. 31 and FIG. 32, it is to be explicitly noted that, if there are defective sectors on two or more different tracks on the same disk surface, it is not necessary that these defective sectors be located “below each other,” i.e., that they are located in the same circle sector. The two or more defective sectors are depicted below each other in the drawings for better illustration. However, the two or more defective sectors may be located at different locations anywhere on their respective tracks. Also, a single track may have several defective sectors at any locations on the track. The guard regions may then cover several defective sectors and “repair” is still possible.

In case the upper or lower half of a band is adjacent to a zone boundary or another boundary which cannot be moved, such as the outer or inner diameter of the disk surface, and in case a defective sector is located in this upper or lower half of the band, it is still possible to “repair” the band by displacing the guard region from the other boundary onto the defective sector.

Moreover, it is possible to shift the boundaries between two zones of the “zone bit recording” to cover a defective sector by a corresponding guard region or gap between the zone boundaries. Shifting zone boundaries may also be done to gain more leeway when adjusting or optimizing the number of tracks per band. Optionally, each zone may comprise one single band, whereby zone 28 and band 18 form a unit that is then jointly shifted, adapted, and/or managed in accordance with defective sectors.

Furthermore, some embodiments may use a variable number of bands. Depending on the distance between defective tracks, i.e., tracks with at least one defective sector, additional bands may be inserted or multiple...
bands 18 may be merged into a “super-band.” The new arrangement of bands 18 may be re-numbered, if desired.  

[0176] Optionally, one or more disk surfaces 2 of the hard disk drive 1 may be divided into areas with overlapping data tracks 17 and areas with conventional, non-overlapping tracks. The areas with conventional, non-overlapping tracks may be used as fast write caches. While the methods according to the present disclosure may be used to “repair” defective sectors 20 in the larger areas with overlapping data tracks 17, a conventional method may be used for the smaller areas with non-overlapping tracks. More information about combining overlapping and non-overlapping areas on a disk surface 2 may be found in the patent application US2014/0006707 A1, entitled “ICC-NCQ Command Scheduling for Shingle-written Magnetic Recording (SMR) Drives,” the disclosure of which is hereby incorporated by reference in its entirety.  

[0177] For illustrative purposes and to keep the number of depicted tracks 3 and physical sectors 4 manageable, all bands 18, zones 28, or other sections of the disk surfaces 2 shown in the drawings of this disclosure comprise relatively few tracks 3 and/or physical sectors 4. It is to be explicitly noted that other actual embodiments can have a very large track count and/or sector count and that all disclosed methods and devices can be implemented with any number of tracks 3 and/or physical sectors 4.  

[0178] The embodiments disclosed herein describe the invention based on the example of an SMR hard disk drive 1. All embodiments and further embodiments can, however, also be implemented by means of other data carrier media, which work, by way of example, on magnetic or optical basis. Among these, band storage is included, which may record according to the shingled magnetic recording methodology. Also, recording data on a data carrier media may be combined or assisted by other known technologies, such as “Heat-Assisted Magnetic Recording” (HAMR), “Two-Dimensional Magnetic Recording” (TDMR), and/or “Bit Patterned Media” (BPM).  

[0179] Although the description above contains many specificities, these should not be construed as limiting the scope of the embodiments but as merely providing illustrations of some of several embodiments. Thus, the scope of the embodiments should be determined by the appended claims and their legal equivalents, rather than by the examples given.  

What is claimed is:  
1. A method for replacing a defective section on a data carrier surface of a storage device configured for overlapping data tracks, comprising placing at least one guard region at least partly onto the physical location of said defective section.  
2. The method of claim 1, wherein said guard region completely covers said defective section.  
3. The method of claim 1, wherein said guard region comprises one single track, multiple adjacent tracks, a single track segment, or multiple track segments on adjacent tracks.  
4. The method of claim 1, further comprising:  
   a) displacing at least one existing guard region onto the physical location of said defective section,  
   b) storing data on the former physical location of said guard region.  
5. The method of claim 4, wherein at least a part of the retrievable data from the track affected by said defective section is stored on the former physical location of said guard region.  
6. The method of claim 4, wherein at least that existing guard region is displaced onto the physical location of said defective section, which is closest to said defective section.  
7. The method of claim 4, further comprising shifting the boundaries of adjacent bands, so that the corresponding guard region gets positioned on said defective section.  
8. The method of claim 7, wherein the width of said adjacent bands is increased or decreased by the number of tracks, by which said guard region is displaced.  
9. The method of claim 4, further comprising displacing stored data, which is located on tracks in the semi-open interval, starting from the former physical location of said guard region up to and including the new physical location of said guard region, by a number of tracks derived from the width of said guard region, preserving the sequential order of said stored data throughout.  
10. The method of claim 4, wherein in the case that two or more defective sections are located in a band on different tracks, which are too far apart from one another to be covered by the width of a single guard region, both the upper and the lower boundaries of said band are shifted, the corresponding upper guard region and the corresponding lower guard region being respectively placed onto the physical locations of said defective sections.  
11. The method of claim 4, wherein in the case that two or more defective sections are located in a band on adjacent tracks, whose combined width is too large to be covered by a single guard region, both the upper and the lower boundaries of said band are pulled together entirely, the corresponding upper guard region and the corresponding lower guard region being placed next to each other on said adjacent tracks affected by said defective sections.  
12. The method of claim 4, further comprising equalizing the track count of a band by shifting the boundaries of adjacent bands to such an extent that the difference in the track count of said band is reduced.  
13. The method of claim 1, further comprising:  
   a) placing at least one additional guard region onto the physical location of said defective section,  
   b) storing existing or future data, originally assigned to said defective section, in a reserve area instead.  
14. The method of claim 1, further comprising:  
   a) scanning or testing the quality of at least one data carrier surface,  
   b) determining the quality of each track,  
   c) placing, by means of an optimization algorithm, guard regions preferentially onto tracks of poor or marginal quality.  
15. The method of claim 1, further comprising:  
   a) detecting defective sections on the tracks of at least one data carrier surface,  
   b) counting the number of defective sections per track,  
   c) placing, by means of an optimization algorithm, guard regions preferentially onto tracks which contain an elevated number of defective sections.  
16. The method of claim 1, wherein  
   a) said storage device is a hard disk drive which operates according to the shingled magnetic recording methodology,  
   b) said data carrier surface is a disk surface of said hard disk drive,  
   c) said overlapping data tracks are grouped into bands and are separated by guard regions in accordance with the shingled magnetic recording methodology,  
   d) said defective section is a defective sector.
17. A data carrier surface having an optimized storage capacity, comprising:
   a) a plurality of overlapping data tracks, grouped into bands,
   b) at least one defective section,
   c) at least one guard region placed at least partly onto the physical location of said defective section.

18. The data carrier surface of claim 17, wherein said guard region completely covers said defective section.

19. The data carrier surface of claim 17, wherein said guard region comprises one single track, multiple adjacent tracks, a single track segment, or multiple track segments on adjacent tracks.

20. The data carrier surface of claim 17, further comprising:
   a) a number of defective sections arbitrarily distributed across the plurality of tracks,
   b) a plurality of guard regions positioned as often as possible on tracks of poor or marginal quality.

21. The data carrier surface of claim 20, wherein the positions of said guard regions are optimized by means of an optimization algorithm, taking into account:
   a) a minimum and/or a maximum permissible number of tracks per band and/or
   b) the quality level of each track and/or track sections and/or
   c) the quality level of adjacent tracks and/or adjacent track sections and/or
   d) the size, the width, or the severity level of a defective section.

22. The data carrier surface of claim 17, further comprising:
   a) a number of defective sections arbitrarily distributed across the plurality of tracks, each track containing several defective sections, a single defective section, or no defective sections,
   b) a plurality of guard regions positioned as often as possible on tracks with an elevated number of defective sections.

23. The data carrier surface of claim 17, wherein the width of each guard region is adjusted individually depending on the size, the width, or the severity level of the defective section covered by said guard region and/or depending on the quality level of adjacent tracks or track sections, subsequent tracks being shifted corresponding to the adjusted width of said guard region.

24. The data carrier surface of claim 17, wherein
   a) said data carrier surface is a disk surface of a hard disk drive which operates according to the shingled magnetic recording methodology,
   b) said overlapping data tracks are recorded according to the shingled magnetic recording methodology,
   c) said defective section is a defective sector.

25. A storage device configured for overlapping data tracks, comprising:
   a) at least one data carrier surface,
   b) a plurality of tracks on each data carrier surface grouped into bands and separated by guard regions,
   c) an optimized number of tracks for each band, individually for each data carrier surface, such that the guard regions are positioned, as often as possible, on tracks of poor or marginal quality.

* * * * *