Functional Materials for Optical Data Storage

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In the current data age, the fundamental research related to optical applications has been rapidly developed. Countless new-born materials equipped with distinct optical properties have been widely explored, exhibiting tremendous values in practical applications. The optical data storage technique is one of the most significant topics of the optical applications, which is considered as the prominent solution for conquering the challenge of the explosive increase in mass data, to achieve the long-life, low-energy, and super high-capacity data storage.

optical data storage functional materials nanoparticles graphene diarylethene

1. Introduction

The unavailable long-life, low-energy, super high-capacity, and renewable and sustainable optical data storage remains a severe challenge to be conquered, which promotes researchers to spare no efforts in designing and fabricating novel systems using more remarkable optical storage materials [1][2][3][4][5]. So far, the total amount of annual data produced globally has increased very fast, which has doubled every two years since 2000 [6]. The traditional technologies including magnetic storage and electrical storage have been improved to deal with the explosive growth of mass information; however, the commercialized products are mainly developed via the two technologies with limited capacity, and the strategies for expanding capacity have reached a bottleneck that is extremely hard to be broken [7][8]. Moreover, the serious drawbacks such as strict storage conditions, the high energy consumption of equipment, and low-security level have restricted the further improvement of magnetic storage and electrical storage, which are difficult to adapt to the booming information era [9][10]. Optical storage materials have been one of the most common recording mediums since the beginning of the 21st century, accompanied by the rapid development of laser technology. Optical storage is the technology that is based on the interaction between laser and recording medium, and the investigation on breaking the diffraction limit for conquering the challenge of present data storage has attracted extensive attention in information technology industry [11]. Compared to the traditional means, optical storage technology shows more possibility for satisfying the requirements of data storage equipped with the properties including large capacity, high safety, intense stability, reasonable price, and low energy consumption [12]. In the past decade, researchers have devoted themselves to exploring new functional materials to be applied in recording media. Meanwhile, the representative recording media such as rare-earth doped upconversion nanoparticles (UCNPs) [13][14][15][16][17], graphene derivatives (GDs) [18][19][20][21], and diarylethene derivatives (DTDs) [22][23][24][25][26] are the most potential materials to be further investigated, which are promising to facilitate the development of optical storage technology and exploit valuable strategies for practical applications and industrialized projects [27][28][29][30][31][32].

The low-energy near-infrared light can be transferred to high-energy UV light or visible light by using the functionalized UCNPs, which is developed for the applications in photolithography, photothermal therapy, photoswitch, and optical storage [33][34]. The UCNPs possess distinct fluorescence properties, which can be incorporated into luminescent materials such as quantum dots, organic dyes, and aggregation-induced emission luminogens (AIEgens) to fabricate novel recording materials equipped with large memory capacities. In comparison with common organic fluorescence chromophores, the UCNPs possess wider energy levels to further reduce transition rates, enabling the low power-assisted stimulated emission depletion (STED) effects to play a crucial role in optical storage [35].

So far, the standardization production of graphene has received remarkable achievements, and the representative industrial process derived from chemical vapor deposition and epitaxial growth has gained rapid development [36][37][38]. In order to overcome the challenge of production modes, the architecture of graphene-based materials like graphene nanobelt and graphene quantum dots has been widely reported to be applied in the construction of field effect transistors, bioimaging, and optical writing [39]. Thus, the significance of designing new graphene nanostructures is in urgent need to cooperate with super-resolution microscopy technology, for the extensive imaging of GD substrates. The majority of receptor systems only can be quenched in a narrowed spectral range; however, the GDs are equipped with the feature of broadband absorption to exhibit energy transfer in the whole visible spectrum, possessing great potential to be introduced in macromolecular systems to prepare composite materials for the application in optical storage [40].

Moreover, on the basis of the established UCNPs, the inorganic–organic hybrid materials are well constructed, combining the merits of UCNPs and organic stimuli-responsive molecules for proposing a new approach to advanced optical storage [41]. The DTDs are the most used organic molecules for optical writing because of their photo-isomerization properties. As the typical photoresponsive molecules, DTDs show vital values in the practical application of the reversible memory assisted by the photoswitched “writing–reading–erasing” [42]. Generally, DTDs can finish the rapid transformation between open and close conformations irradiated by the UV light and visible light, respectively. More importantly, DTDs have favorable physicochemical properties, including strong thermal stability, moderate fatigue resistance, a quick responsiveness and reaction rate, a high-conversion ratio of open/close isomers, sufficient quantum yield, and an obvious difference of absorption wavelength between the open/close isomers. The DTD-based composites play a crucial part in optical storage owing to their significant changes of absorption spectra, dielectric constants, and geometrical configuration, and have tremendous commercial values for optical storage revolution in the future [43][44][45].

The optical storage materials are one of the most promising recording media in the digital age [46]. Researchers have been sparing no efforts on the in-depth exploration of the three functional memory materials for pursuing a larger storage density [47][48][49][50][51]. According to the strategies of increasing the number of layers, enhancing the recording dimensions of recording media, and narrowing the diffraction limit, researchers envision that the ultrahigh storage density of the TB level, even PB level, will eventually be approached in a single disc [6][52].

2. Upconversion Nanoparticle-Based Functional Materials

The technology of high-density optical writing is of great significance in data storage. Additionally, the optical writing technology at nanoscale level based on the far-field super-resolution method provides a unique approach for dealing with memory devices with a large capacity. However, the current nanoscaled optical writing measures generally rely on the mechanism of photo-initiation and photo-inhibition, which seriously restricts their further development due to the disadvantages of the high intensity of laser, large consumption of energy, and short life of devices [53]. Notably, the UCNP-based systems have broad excitation levels to decrease transition rates. Meanwhile, according to the far-field super-resolution technology, the electron transition in UCNP-based systems can be selectively modulated to activate the energy transfer-derived low-power radiation for breaking through the diffraction limit in optical writing. In this section, the diverse UCNP materials used for optical writing and optical storage with particular functions are discussed in detail (**Table 1**).

Table 1. UCNP-based functional systems for optical storage applications.

UCNP-Based Systems	Methods of Preparation	Properties	Ref.
UCNPs-1	Sol–gel pyrolysis technique	Stimulated absorption mechanism and emission in the range of visible light	[54]
UCNPs-2	Solvothermal method	Reducing the requirement of optical depletion for laser intensity	[55]
UCNPs-3	Oxygen-free hydrothermal protocol	Background-free and ultrahigh-sensitivity imaging	[56]
$NaYF_4$ nanocrystals	Solvothermal method and crystal growth	Precise control of phase, size, and optical emission features	[57]
Different phases of $NaYF_4$:Yb,Er	Thermal decomposition of metal oleate precursors	Defect-reduction strategies of preparing small and brighter UCNPs	[58]
UCNPs-4	Solvothermal method	Realizing the 28 nm super high-resolution	[30]
Lifetime-coded microspheres	Electrostatic interaction	Enlarging the optical multiplexing range by increasing the time dimension	[59]

3. Graphene-Based Functional Materials

Graphene is a 2D crystal that resembles as hexagonal network structure with the thickness of a single atomic layer, which is constructed from the tight arrangement of sp^2 hybrid carbon atoms. Owing to the distinct 2D skeleton, specifical energy band structure, and remarkable carrier transport velocity, the graphene possesses broad prospects in memory storage [60]. In addition, GDs derived from graphene such as graphene oxides (GOs) are equipped with abundant carbonyl, hydroxy, and epoxy moieties on the surface, as well as the numerous conjugated units in the intrinsic frameworks, endowing the GDs with intense fluorescent properties for the fabrication of luminescent devices. In this section, according to the admirable photoelectric performance of GDs, researchers introduce the GD-based functional materials for the application in the field of optical data storage (**Table 2**).

Table 2. GDs-based functional platforms for optical storage applications.

GDs-Based Systems	Methods of Preparation	Properties	Ref.
GO-contained UCNPs-5	Coprecipitation method and electrostatic interaction	Resonance-assisted optical writing and ultrahigh capacity optical storage	[61]
MoS_2-based memory device	Mechanical exfoliation and polydimethylsiloxane stamping	High on-off ration, long retention time, stable, and durable features	[62]
Graphene-contained Pr:YAG	Electrostatic interaction	Background-free and ultrahigh-sensitivity imaging	[63]

4. Diarylethene-Based Functional Materials

Precise writing and nondestructive readouts are indispensable features for advanced optical storage. The diarylethene (DTE)-based fluorescent molecular switches can reversibly change between open ring isomer and closed ring isomer states via alternating UV/visible light irradiation, which is equivalent to photocontrollable molecular-scale digital switches for directing the data recording and reading, having promising prospects in high-density optical data storage by virtue of its excellent thermal stability and fatigue resistance [64]. Generally, the wavelength of reading beam for the DTE will participate in the open/closing ring reaction, exerting severe effects for optical writing and reading. Thus, the functional DTDs combining DTE molecules and nanocomposites are fabricated for pursuing accurate recordings and nondestructive readouts (**Table 3**).

Table 3. DTD-based functional materials for optical storage applications.

DTD-Based Systems	Methods of Preparation	Properties	Ref.
UCNPs-6 modified DTE-1	Layer-by-layer epitaxial growth procedure	Highly purified emission and rewritable optical storage	[65]
UCNPs-7 modified DTDs	Electrostatic interaction and self-assembly strategy	Application in scanning near-field optical microscopy for higher storage density	[66]
Ferroelectric crystals with DTE enantiomers	Dropping and spreading the crystal-based precursor on ITO glass substrate to obtain thin film	Achieving a contactless integrated process of writing, reading, and erasing in data storage	[67]
DTE-based Alq_3 complex	Metal complexation	Photocontrolled electron migration and as active layers in resistive memory devices	[68]
DTD-based photoresponsive amphiphilic polymer	Self-assembly strategy	Combination of FRET and emission reabsorption effects	[69] [70]

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