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REVIEW ARTICLE

Progress of super-resolution near-field structure and its application in optical data storage

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Abstract The era of big data has necessitated the use of ultra-high density optical storage devices. Super-resolution near-field structure (super-RENS), which has successfully surpassed the fundamental optical diffraction limit, is one of the promising next generation high-density optical storage technologies. This technology combines the traditional super-resolution optical disk with a near-field structure, and has the advantages of structural simplicity, strong practicability, and, more importantly, compatibility with the current optical storage pickup. The mask layer in super-RENS functions as the key to realizing super-resolution. Development of suitable materials and stack designs has greatly been improved in the last decade. This paper described several types of super-RENS, such as aperture-type, light scattering center-type, bubble-type, and other types (e.g., WO_x and ZnO), particularly the newly proposed super-RENS technology and research achievements. The paper also reviews the applications of super-RENS in high-density optical data storage in recent years. After analyzing and comparing various types of super-RENS technology, the paper proposes the aperture-type based on the mechanism of nonlinear optics as the most suitable candidate for practical applications in the near future.

Keywords super-resolution, near-field, mask layer, optical nonlinear, localized surface plasmas

1 Introduction

The rapid development of information technology has ushered humanity into the era of big data. The demands of this era include high-density, large-capacity, long-life, secure and environment-friendly storage devices. Optical storage is very useful for high-definition TV and mass data storage. However, as the demand for ultra-high density optical storage devices continues to grow, information pit size must be continuously reduced to improve recording density. The resolution of conventional far-field optics is mainly restricted by the diffraction limit $D \propto \lambda/\mathrm{NA}$, where D is the focusing spot diameter, λ and NA are the laser wavelength and numerical aperture of the objective lens, respectively. To achieve ultra-high density storage, λ must be reduced and NA increased to reduce the mark size. However, the laser wavelength in current far-field storage devices has been decreased from 780 nm for compact disc to 405 nm for Blu-ray disc. Efforts to further reduce laser wavelength are limited, because of the difficulty of developing laser devices and low transmission of general optical elements at wavelengths below 360 nm. Moreover, NA has already been developed close to its limit (NA = 1); for example, the NA for Blu-ray optical pickup has reached 0.85. Thus, any further increase will reduce the focal depth of the pickup and increase chromatic aberration when the disc tilts against the optical axis [1].

Many near-field techniques have been proposed in recent years to overcome the fundamental diffraction limit. The term “near-field”, as opposed to “far-field”, refers to the electromagnetic field that consists of several to tens of nanometers from the surface of the samples. The largest difference of near-field from far-field is that it contains high-frequency Fourier component information, which corresponds to the fine structure of the described objects. Among near-field techniques, near-field scanning optical microscopy (SNOM) [2] and solid immersion lens (SIL) have become hot research [3]. Although SNOM has a high spatial resolution, it is beset by certain disadvantages in its applications, such as low optical transmission and difficulty in controlling the near-field distance between the probe tip and sample surface during high-speed rotation. SIL can also obtain a subwavelength spot and

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produce nanoscale marks. Furthermore, it can maintain a higher optical transmission than SNOM. However, the problem of near-field distance control between the lens surface and sample remains.

To overcome the difficulties that limit these two technologies, Tominaga et al. proposed the super-resolution near-field structure (super-RENS) technology in 1998 [4], which combines mask super-resolution technology [5] with a near-field structure. Super-RENS technology has undergone considerable development in the last decades, which has the ability to break through the optical diffraction limit as well as the capability to realize recording and readout of below-diffraction-limited information marks. Various functional mask materials and near-field structures, such as antimony-based (Sb-based) phase change thin films [6–9], metal oxides [10,11], metal-dielectric nanocomposite films [12–14], and others have been recently reported; they can be roughly classified into several typical types depending on their write/read mechanisms. This paper describes various types of super-RENS and introduces their applications in optical data storage, particularly the recently proposed super-RENS technology and its related research achievements.

2 Types of super-RENS technology

2.1 Aperture-type super-RENS

Figure 1 shows a schematic of the classical aperture-type super-RENS technology. A polycarbonate disk is used as a substrate, and grooves with a track pitch of 1.2 μm are fabricated on the surface. The Sb thin layer in a sandwiched structure between two SiN protective layers is utilized as the mask layer, and $Ge_2Sb_2Te_5$ is used as the recording layer. The Sb thin film responds nonlinearly when irradiated by a focused beam spot with Gaussian intensity profile, which subsequently causes the formation of a subwavelength transparent aperture within the near-field region of the sample. The below-diffraction-limited spot (super-resolution spot) through the aperture acts on the recording layer, and a recording mark is fabricated. The Sb film then instantaneously recovers its original state when the laser beam is removed, and a near-field recording process is completed. Structures with such characteristics are called aperture-type super-RENS, which utilizes a nanoscale nonlinear functional thin film and an ultra-thin dielectric film to achieve a nanoscale aperture similar to the near-field probe tip and to control the nanoscale space between the tip and sample. The most important advantage of super-RENS is the air space between the probe and the recording medium layer, which is replaced by a dielectric film. The thickness of the film can be precisely controlled by sputtering or other vacuum technologies, thereby skillfully solving the problem of servo control.

In 1999, Fukaya et al. regarded the Sb mask layer as an optical switch [15]. They found that an instantaneous light-induced aperture forms in a Sb film with a pulse laser light irradiation of 10 μs, and that it rapidly "opens" or "closes" with the irradiation spot. In 2000, Tsai and Lin observed the near-field optical nonlinear properties of the SiN/Sb/SiN of the super-RENS through a tapping-mode tuning-fork near-field scanning optical microscope in transmission mode [16]. They found both propagating and evanescent field intensities at the focused spots on the surface of the sample, which they attributed to the localized surface plasmas at the Sb/SiN interface. Tominaga and Tsai investigated the origin of the super-resolution effect and claimed that the phase change induced by the photo-thermal effect at the center of the spot of Sb film generates a transparent aperture. They also claimed that the localized surface plasmas excited at the Sb/SiN interface produce a near-field localized field enhancement.

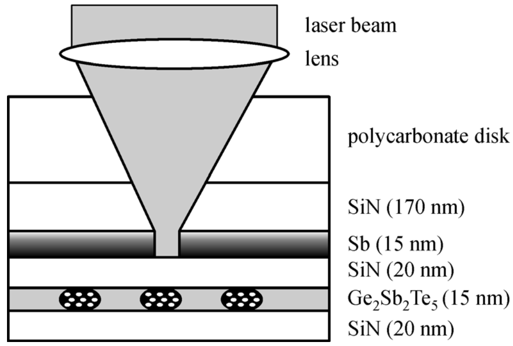


Fig. 1 Schematic of the super-RENS disk structure and near-field recording [4]

To ascertain how nano-sized apertures are formed, Simpson et al. investigated aperture formation with Sb, Sb_2Te_3, Sb_2Te, and SbTe by using time resolved optical pump-probe techniques; they found that no melting occurred in the process [17]. The optical power incident on the film can be increased by steps of 1.2 mW from 11 to 38 mW; the performance of the four materials is shown in Fig. 2. Simpson et al. identified four distinct regions: (1) no change in transmission, (2) a temporary high transmission state, (3) a low transmission state, and (4) a permanent, high transmission state. Region (1) indicates that the laser has no measurable effect on the transmission of the materials. Regions (2) and (3) indicate the presence of the super-RENS effect, that is, a temporary, and high transmission state is activated during the irradiation from the pump laser. However, once the pump is switched off, the transmitted intensity decreases rapidly. Region (4) is synonymous with amorphization of the crystalline state, that is, sufficient laser energy is provided to the Sb-Te film, thereby melting the film. Once the laser heat source is removed, the film rapidly stabilizes into a transmissive amorphous state, in other words, the film is damaged. A permanent amorphous area (region 4) forms in all the samples, except in the pure Sb film, when the incident laser power is sufficient to melt the material. Reducing the incident power causes the transient super-RENS effect (region 2), but the materials do not melt. The resonant bonds that exit the crystalline phase-change materials are considered the determining factors of the optical properties of the materials. The thermal vibration of the atoms is insufficient to destroy the resonant bonds when the temperature rises. However, the resonant bonds are weakened only to result in a low absorption coefficient, allow the light to pass through the materials, and obtain a temporary, highly transmissive state. The resonant bonds return to their original state when the temperature decreases.

Lu et al. reported that $Sb_{98}Bi_2$ thin films can be used as the functional mask for super-resolution ROM disks with a pit length of 390 nm [18]. Disc readout is conducted by a dynamic tester with a laser wavelength of 780 nm and an NA of 0.45. A carrier-to-noise ratio (CNR) of 22 dB can be obtained at a low power of 0.8 mW, as is usually the case in almost all approaches to the readout power of traditional optical disks.

Recent years, there have seen significant progress in super-RENS technology applications. Nakai et al. fabricated a 46 GB super-RENS ROM disc with a five-layered structure, which includes the InSb mask layer sandwiched between the ZrO_2 interface layers and features a minimum pit length of 80 nm, as shown in Fig. 3(a) [19]. They experimentally evaluated the bit error rate (BER) and obtained a BER of approximately 1.3×10^{-5}, which is below the criterion of 3×10^{-4}. They further demonstrated that the disk sample remains stable after readout of more than 4×10^5 times. They subsequently achieved the first seamless real playback of an HD video content from a 50 GB super-RENS ROM disc with the same five-layered structure. Figure 3(b) shows a snapshot of the playback demonstration [20]. Nakai et al. increased the radial density by introducing a narrow track pitch that corresponds to the diffraction limit set in 2013, which is 1.33-times that of the BD physical format. They simultaneously confirmed that differential phase detection can identify track errors from disc samples recorded with random data and with a minimum pit length of 75 nm in a 240 nm track period; they obtained a BER value below the criterion of 3×10^{-4} [21].

Wei recently suggested that the optical nonlinear properties of mask thin films are critical in obtaining the

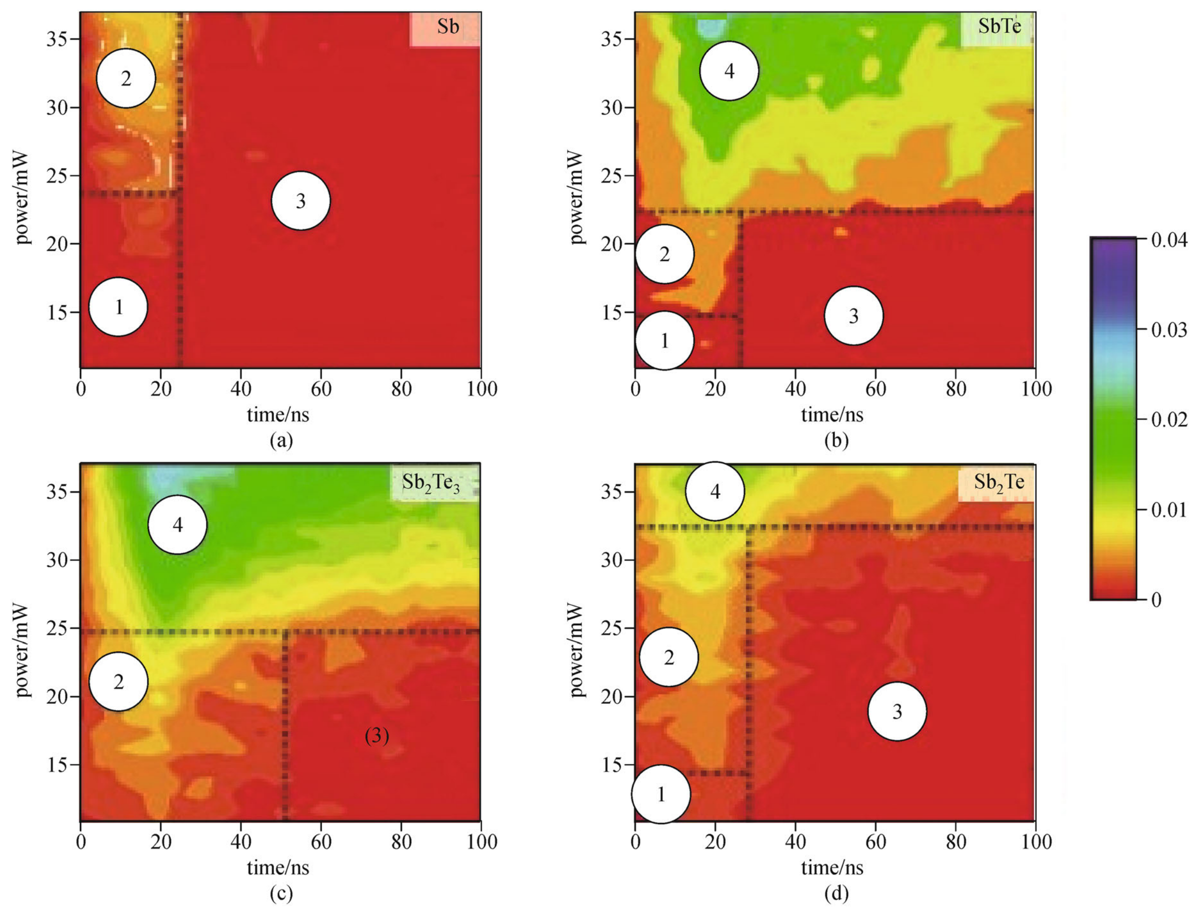
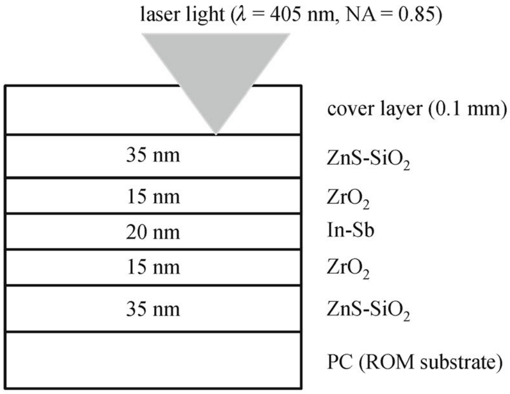
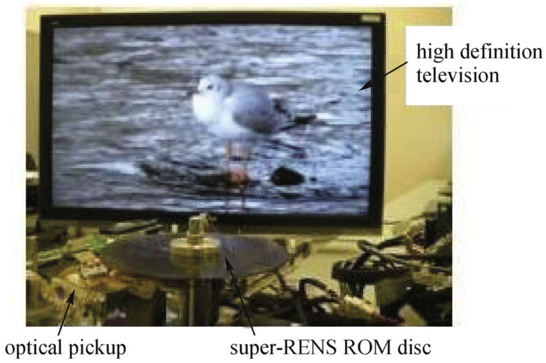


Fig. 2 Power-time-transmission plot of crystalline Sb-Te samples [17]. (a) Sb; (b) SbTe; (c) Sb_2Te_3; (d) Sb_2Te



(a)



(b)

Fig. 3 (a) Structure of In-Sb super-RENS ROM disk [19]; (b) snapshot of playback demonstration of HD video content from In-Sb super-RENS disk [20]

super-resolution spot [22]. Optical nonlinearity generally includes the two aspects of nonlinear refraction and nonlinear absorption. Positive nonlinear refraction can induce a self-focusing effect, which can nevertheless have a negligible contribution because of the focal length beyond the thickness of the mask layer. By contrast, positive nonlinear absorption directly produces an effective energy absorption spot and then forms a super-resolution information mark on the recording material; for example, AgInSbTe is a typical reverse-saturable absorption material with a positive nonlinear absorption coefficient, which can be used in nanoscale data storage when combined with the thermal threshold effect [23].

However, negative nonlinear absorption (nonlinear saturable absorption) has a dominant role throughout most of the super-RENS recording and readout procedure. In the case of nonlinear saturable absorption materials, a high laser intensity results in a large transmittance, which, in turn, produces a super-resolution optical aperture in the central region of the spot. Substantial z-scan measurements have shown that the effective nonlinear absorption coefficient of most Sb-based alloy materials can reach up to 10^{-2} m/W [24–27]. Figure 4 shows the z-scan measurements for a Sb_2Te_3 thin film at a laser wavelength of 405 nm with a laser pulse width of 100 ns, and a laser intensity of 1.8×10^8 W/m^2. The fitting results indicate that the Sb_2Te_3 thin film produces the nonlinear saturable absorption effect, with a nonlinear saturable absorption coefficient of $\beta = -5.2\times10^{-2}$ m/W, which is a large value [28].

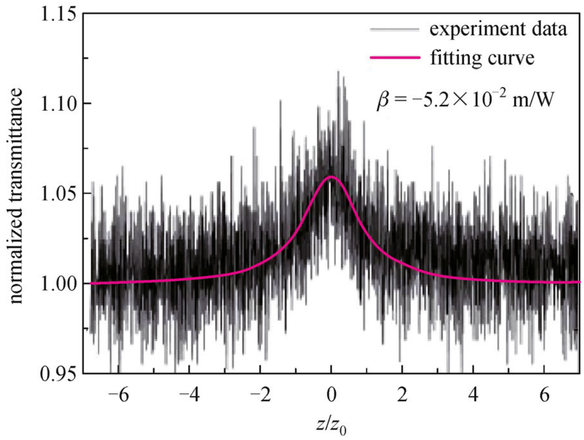


Fig. 4 Z-scan measurement results for Sb_2Te_3 thin films [28]

After various researchers achieved super-resolution recording or readout through the application of nonlinear optical materials, Wei et al. innovatively combined the saturation absorption and reverse saturation absorption in a super-resolution structure and obtained a remarkable achievement [28]. In the structure presented in Fig. 5, the Sb_2Te_3 thin film is used as the mask layer, and the dye layer with reverse saturation absorption characteristics and thermal threshold effect is used as the recording layer. Both characteristics of the recording material significantly reduce the recording marks. Information recording and readout were conducted by the testing system, in which the laser wavelength was 405 nm and the NA of the optical pickup was 0.65. The experimental results indicated that information marks below 100 nm are recorded and read out at a recording power of 5 mW and a readout power of 1.5 mW. Moreover, minimum marks of 60 nm are realized, which is only about 1/3 of the dynamic readout resolution limit ($d=\lambda/4$NA).

The aperture-type super-RENS has been systematically studied for a long time, and given its nonlinear optical characteristics, no deformation was found to be generated in the procedure. That is, no stress results in good stability, which is favorable for realizing enhanced longevity. Moreover, the combination of reverse saturable absorption materials as the recording layer is not merely read-only but also recordable. This method is currently the only procedure to have achieved real playback of an HD video content for dynamic readout super-RENS technology. We therefore have reasons to believe that this technology is the most practical scheme.

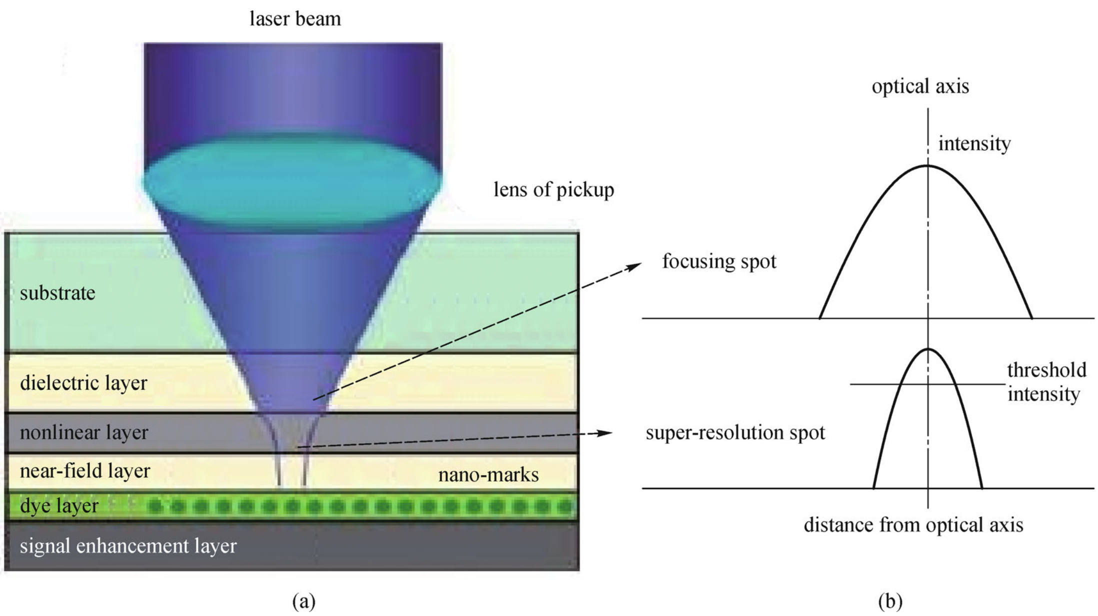


Fig. 5 Schematic and principle of nano-optical information storage: (a) sample structure; (b) optical spot intensity profile [28]

2.2 Light scattering center-type super-RENS

Fuji et al. proposed a new super-RENS that uses AgO_x thin film as the mask layer to further enhance the signal intensity [10]. Figure 6 shows the cross section of AgO_x super-RENS disks. Their experimental results indicated that small marks of less than 100 nm in length can be recorded and reproduced by the optimized AgO_x layer at 6.5 and 2.5 mW, respectively. In this structure, AgO_x layer is used to produce the metallic probe, which is supposed to decompose into nano-sized Ag particles and oxygen via a photo- or thermal-chemical reaction. Given the lack of experimental observation, the researchers suspected that this process is reversible in its early stage, but many studies have revealed that this process is irreversible. The Ag nanoparticle has always been regarded as a light scattering center, and the near-field light is generated around it. This near-field light interacts with the recording layer, and small marks can be recorded and reproduced. The signal is enhanced by the surface plasma excited by the Ag particles under laser irradiation, which is beneficial to write/read fine super-resolution marks.

Her et al. studied the recording and readout mechanism of the AgO_x super-RENS disk [29]. Figure 7 reproduces the transmission electron microscopy (TEM) images of $ZnS\text{-}SiO_2/AgO_x/ZnS\text{-}SiO_2$ films being irradiated by a 405 nm blue laser. A hollow Ag cylinder or ring, which serves as an aperture, is formed at various flow ratios, but small Ag particles are precipitated at the center of the region during the recording process and are detected only at flow ratios of 0.5 and 0.7. Both of the Ag cylinder and ring can significantly reduce the laser spot size during the readout process, whereas a much higher CNR was detected in the super-RENS disks that generated the Ag particles. Her et al. believe that the readout signal can be further improved with the aid of a localized surface plasmon coupling effect between precipitated Ag particles and subwavelength marks that yield strong near-field intensity.

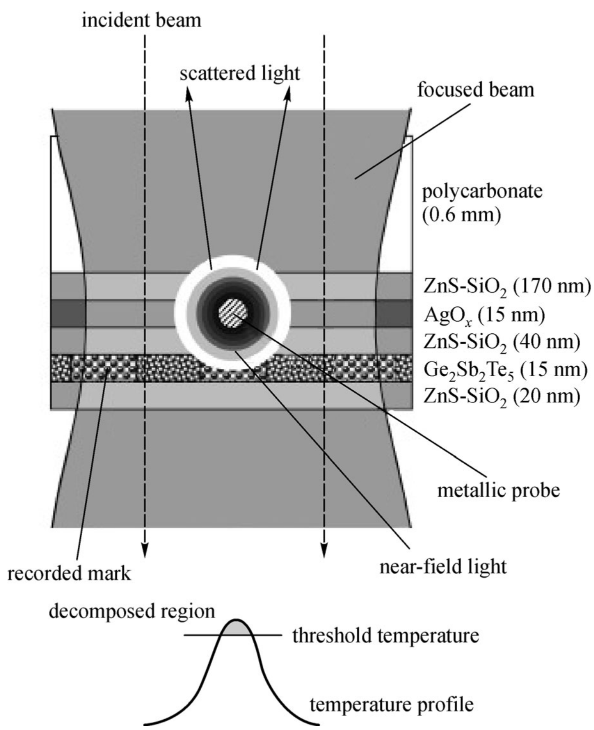


Fig. 6 Cross section of an AgO_x super-RENS disk [10]

Li et al. used the finite-difference time-domain (FDTD) method to analyze the scattering fields from the localized

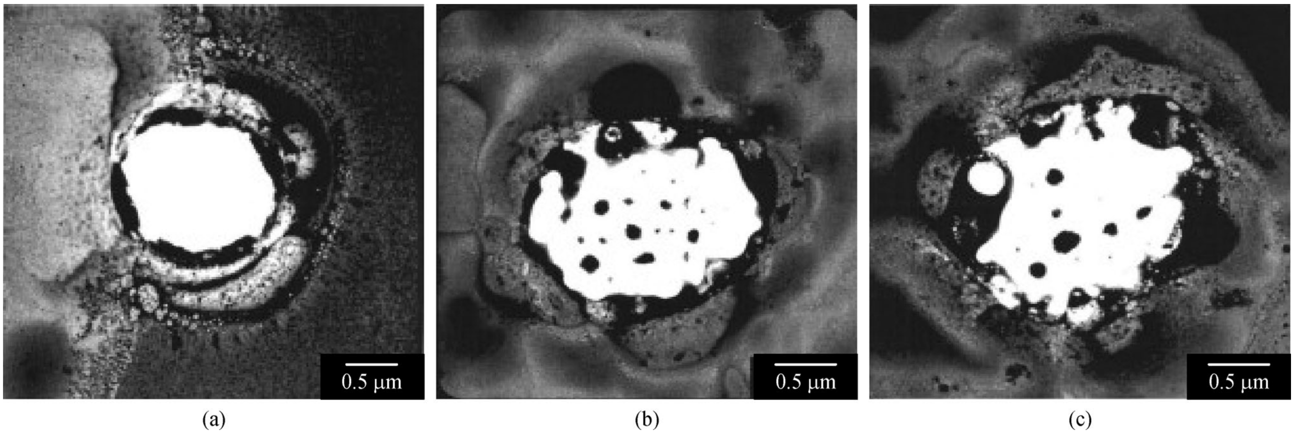


Fig. 7 TEM images of $ZnS-SiO_2/AgO_x/ZnS-SiO_2$ films after being irradiated by a blue laser pulse with a power of 7 mW at a duration of 1 μs [29]: (a) 0.2; (b) 0.5; (c) 0.7

surface plasmons (SP) of Ag nanoparticles [30]. The study of near-field characteristics shows that the SP enhancement induced by Ag nanoparticles is limited to the mask layer and that the spatial extension of the evanescent field is very short along the thickness direction of the mask layers. Li et al. believe that the reflective elastic scattering, rather than the SP effect, is the mechanism of the signal enhancement of the super-RENS disk with metal nanoparticles.

Chou used a 3D-FDTD model to study the surface plasmon resonance (SPR) effects between solid silver and Ag-shell nanoparticles (MNPs) of the Ag mask layer [31]. He found that the square Ag-shell of MNPs has the highest field intensity that corresponds to SPR wavelengths and that the bubble pits formed in AgO_x mask layer can provide an additional propagation path and further excite evanescent fields.

Fu et al. introduced an $Au-SiO_2$ nanocomposite thin film as a novel mask layer for the super-RENS [12]. The z-scan results of these nanocomposite films indicate their nonlinear optical properties and strong enhancement in transmittance. An Au nanoparticle sample with an average grain size of 5 nm results in the greatest enhancement in terms of transmittance (135%). Fu et al. supposed that the key factors behind these results lay in the excitation of the localized surface plasmons of the Au nanoparticles and the optical interactions between them.

Polysilicon is characterized by a self-focusing effect when excited by the laser source and at the same time exhibits a reverse saturable absorption. These two features have opposite roles with respect to the laser beam. Wei et al. designed a silver-doped silicon thin film and used it as the mask material; it was found to have a self-focusing effect and saturable absorption characteristic that enhance its transmittance [13]. Their experimental results show that an absorption peak occurs at a wavelength of about 400 nm and that the excitation at 415 nm can be identified as the surface plasmon resonance absorption peak, which is caused by the resonance absorption of the surface plasmon between the metal particles and matrix. The *z*-scan measurements also indicated that the Ag-Si nanocomposite thin film has a large saturable absorption and that the absorption coefficient decreases as the laser intensity increases to produce a super-resolution effect. Zhao et al. subsequently used the Ag-Si nanocomposite thin film as the mask layer in the ROM disk and read out a small mark beyond the optical diffraction limit [14].

A new method has recently proposed by Wang et al. to optically synthesize Ag nanoparticles in a phase change matrix [32,33]. This method is a potential approach to forming a simpler plasmonic recording structure than the traditional AgO_x-type structure.

The phase change chalcogenide microstructures with embedded Ag nanoparticles can be prepared through irradiation of a nanosecond laser pulse on a $Ge_2Sb_2Te_5$/Ag bi-layer structure. Figure 8 shows the TEM images of silver-nanoparticle-embedded $Ge_2Sb_2Te_5$ phase change recording pits. A laser pulse with appropriate power and duration leads to record pits with a random distribution of Ag nanoparticles, as shown in Fig. 8(a). With a laser pulse of increasingly high influence, a distribution of ring Ag nanoparticles can be obtained, as shown in Fig. 8(b).

An enhancement signal in this structure is gained for the enhanced localized near-field around the Ag nanoparticles. Meanwhile, an increased quantity of propagation-ready information about the optical contrast between the recorded and non-recorded areas can be obtained through the localized SPR of Ag nanoparticles near or in the recording pits. Both aspects can improve the far-field resolution. The near- and far-field optical properties of the nano-composite phase change recording pits can be adjusted easily, because the complex refractive index of phase change materials can be precisely controlled by laser irradiation under different conditions. Furthermore, different metal nanoparticle-embedded recording pits can be formed by using different matrix materials and the appropriate metal dopant. Given that, the silver nanopar-

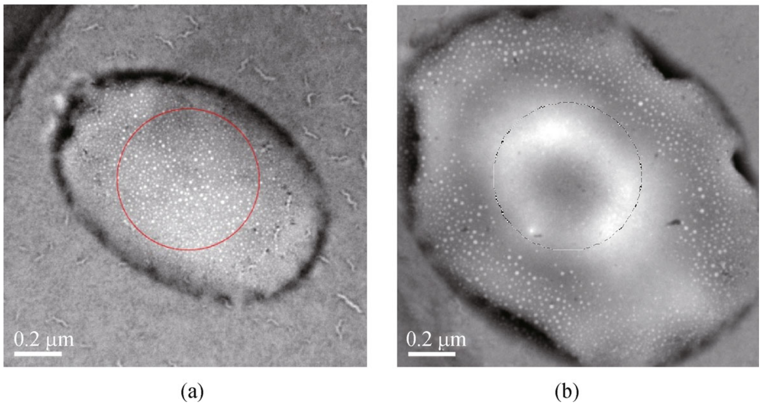


Fig. 8 Bright-field TEM images of the silver-nanoparticle-embedded phase change recording pits with different laser power and pulse width [32]: (a) random Ag nanoparticles distribution; (b) ring Ag nanoparticles distribution

ticles are dispersed in the chalcogenide phase change matrix rather than in the oxide bubbles, their readout and environmental stability are greatly enhanced relative to those of the traditional metal oxide type super-RENS. This type of super-RENS technology may be suitable for long-life data storage.

Light scattering center-type super-RENS has been substantially investigated. This type of technology features high resolution. However, chemical reactions occur in the process of the AgO_x type, followed by deformation. Meanwhile, the deformation temperature of AgO_x is low. All these disadvantages result in instability, which short-changes the advantage of longevity. However, the recently proposed Ag-Si nanocomposite and silver-nanoparticle-embedded types circumvent these problems and can therefore be considered the appropriate approach to long-life super-RENS optical storage.

2.3 Bubble-type super-RENS

Given the instability of AgO_x at high temperature, researchers have attempted to find suitable substitutions. Studies with such objectives have found a strong correlation between light scattering by surface plasmon and nanoparticles size. Therefore, any further improvement of signal intensity depends on generating increasingly small metallic nanoparticles in the super-RENS system. In 2002, Kikukawa et al. first proposed using a PtO_x layer in the super-RENS disk, whose decomposition temperature is higher than that of AgO_x and is expected to produce increasingly small Pt particles [34]. In the experiment, a $(ZnS)_{85}(SiO_2)_{15}$ (130 nm)/PtO_2 (4 nm)/$(ZnS)_{85}(SiO_2)_{15}$ (40 nm)/$Ag_{6.0}In_{4.5}Sb_{60.8}Te_{28.7}$ (60 nm)/$(ZnS)_{85}(SiO_2)_{15}$ (100 nm) multilayer structure was deposited on a polycarbonate substrate. Rigid bubble pits were formed by O_2 gas released by the decomposition reaction of $PtO_x \rightarrow Pt + x/2O_2$ with the application of the write power, and permanent deformations were generated on the dielectric and recording layer. The Pt nanoparticles were scattered in the bubble pits at the readout procedure, and localized surface plasmons formed around them. Bubble pits with a size of 200 nm rigidly formed and were well separated, and platinum particles with a size of 20 nm were precipitated inside the bubble. The cross section of the mark trains was also observed through TEM, as shown in Fig. 9. The signal enhancement is assumed to have been caused by the local-field coupling with the phase change layer induced by the high readout power irradiation. The results of the experiment showed that the CNR for 200 nm long marks can reach up to 46.1 dB, and it does not change even after a readout of 3×10^4 times. The writing and readout power are 10 and 4 mW, respectively. A CNR of 42.3 dB can be obtained even for 150 nm long marks. Liu et al. also reported on the PdO_x mask layer, which is similar to PtO_x [35].

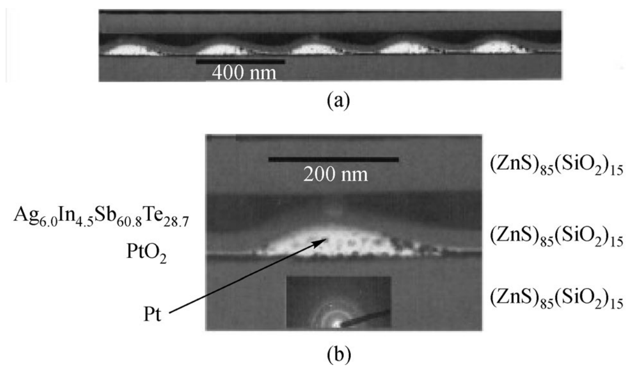


Fig. 9 (a) TEM bright-field images recorded at 10 mW and subsequently readout by 4 mW sample and (b) magnified bubble pit [34]. The inserted image in (b) is the selected area of the electron diffraction patterns around the recorded pits

The bubble-type super-RENS can be divided into two types based on the shape of the recorded bubble of the PtO_x layer. The traditional structure has a single AgInSbTe layer and a bubble of a semicircular type, as shown in Fig. 10(a) [36]. In 2003, Kim et al. reported an elliptical bubble-type super-resolution structure [37], which has a symmetrical form and two AgInSbTe layers, as shown in Fig. 10(b). The change in the elliptical volume is caused by the generation of gas pressure and deformation of the two ductile AgInSbTe layers. This type of super-RENS also has a higher CNR than the semicircular type. Its CNR of over 47 dB for 100 nm mark length signals was determined, and the recording and readout power were 11.5 and 3.5 mW, respectively. Its CNR of over 43 dB for 80 nm mark length signals was also determined and was considered the commercially acceptable level. Kim et al. believe that the surface plasmon scattering light interacts with the upper and lower AgInSbTe layers and creates the large signal enhancement in the readout process, and that the PtO_x layer acts as a recording layer rather than a mask layer. Some researchers have recently begun to think that the AgInSbTe layer in this structure is used to reduce the recording spot because of the significant reverse saturation absorption.

Shima et al. applied the super-RENS technology in a high definition digital versatile disk (HD-DVD) based system with double PtO_x layers [38]. A CNR of 45 dB was obtained for the 100 nm long marks, and the recording and readout power were 10.5 and 2.8 mW, respectively. A CNR of 40 dB has been obtained for the 60 nm long marks. In subsequent works, SiO_2 was added to the PtO_x layer [39] and the GeNy interfacial layers were inserted between the $Sb_{75}Te_{25}$ and ZnO-SiO_2 layers [40] to significantly enhance the readout durability, which is enhanced by more than one to two-orders-of-magnitude relative to that in the simple PtO_x case.

Liu et al. studied the readout durability of a super-RENS disk based on a simplified PtO_x layer [41]. Their experimental results showed that in an actual PtO_x super-RENS disk, readout durability strongly depends on the stability of the bubble, which is in turn influenced by the recording and readout power, the thickness of the AgInSbTe layer, and the ZnS-SO_2 dielectric layer. As for the super-RENS mechanism, they thought that the bubble structure, which consists of a PtO_x layer and ZnS-SO_2 dielectric layer, looks like the tip used in a scanning near-field optical microscope. The light that passes the tip-like bubble reaches the AgInSbTe layer and causes an AgInSbTe phase transition from an amorphous to crystal form. A schematic of the recorded super-RENS disk is shown in Fig. 11.

Kuwahara et al. studied a super-resolution disk in which

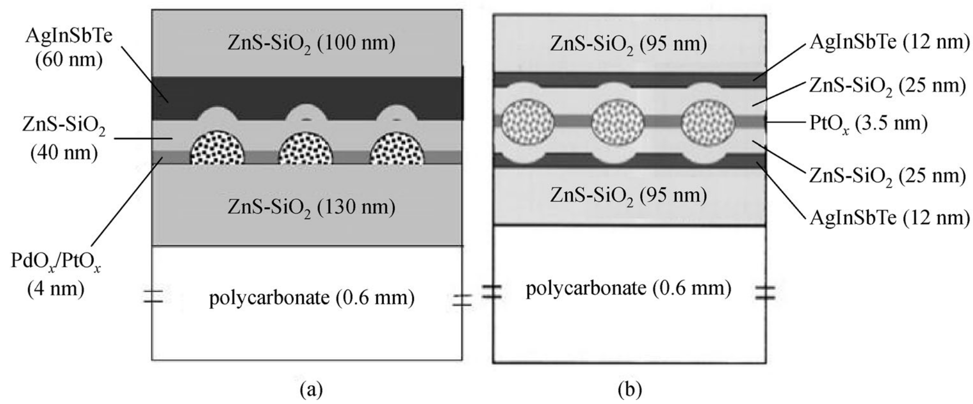


Fig. 10 (a) Semicircular bubble-type super-RENS disk [36]; (b) elliptical bubble-type super-RENS disk [37]

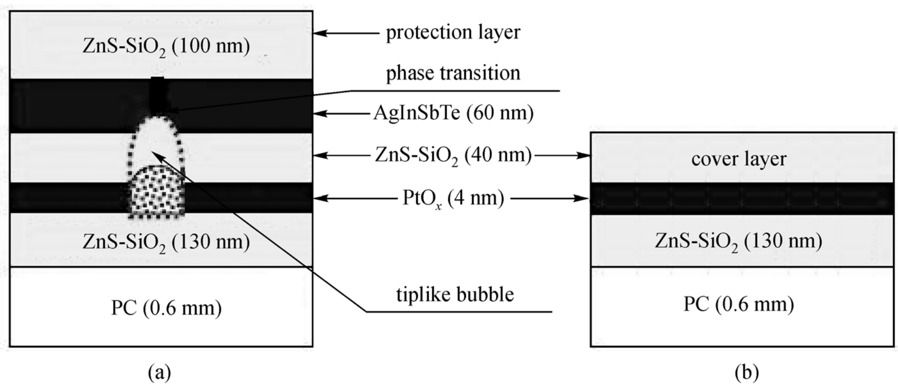


Fig. 11 Schematic of the super-RENS [41]: (a) recorded super-RENS disk; (b) simplified super-RENS

the PtO_x layer was replaced with a metal-free phthalocyanine (H_2Pc) layer to ascertain the presence of Pt nanoparticles, which are important to the readout mechanism [42]. Given the observation that the CNR was equivalent to that of a disk made by using PtO_x, Kuwahara et al. concluded that nanoparticles do not have an important role in the super-RENS readout mechanism.

The bubble-type super-RENS has a higher resolution and stability than the AgO_x mask layer. Optimizing the film structure, results in greatly improved stability and CNR that are close to the commercial standards. However, deformation also occurs during the procedure and affects the service life of the devices. Another disadvantage of this type is its use of a high-priced rare metal.

2.4 Other types of super-RENS

The WO_x thin film, which is used as a mask material, represents a high transition temperature. Kim et al. measured the transmittance change with the temperature increase, and their results showed that changes occur only at 573 and 790 K [43]. Photochromic conversion is assumed to occur in the WO_x mask layer at 573 K and a permanent transition at 790 K. Based on the photochromism effect, higher laser intensity corresponds to larger transmittance of this material, which in turn causes an optical aperture. A combined W recording layer and WO_x mask layer achieves a much higher CNR, lower noise level, and better thermal stability than those of a super-RENS disk with an AgO_x layer in the experiment.

Lin et al. first proposed a ZnO mask layer super-RENS disk in 2003; its structure consists of polycarbonate/ZnS-SiO_2 (130 nm)/ZnO(15 nm)/ZnS-SiO_2(30 nm)/$Ge_2Sb_2Te_5$(15 nm)/ZnS-SiO_2(20 nm) [44]. Its CNR of more than 33 dB was measured for the recorded marks with a size of 100 nm by using a digital versatile disk tester at a readout power of 5 mW.

To clarify the origin of the ZnO super-resolution effect, Mori G et al. examined the characteristics of ZnO thin films by testing the super-resolution effect by using blue- and red-laser optic systems [45]. They found that a reversible and repeatable change occurs in the optical constants (n and k) at the blue-laser wavelength, because the energy gap of ZnO is 3.3 eV (equivalent to a 376 nm wavelength), which is near the blue-laser wavelength. In the experiment, the super-resolution effects were obtained only under the blue-laser optics, and the CNR of 40 dB was obtained at a 160 nm pit length, which was zero for red-laser optics. The principle of these super-resolution effects using a ZnO film is based on the reversible energy gap shift of the film. Thus, this type of super-resolution is called the energy-gap-induced super-resolution (EG-SR).

Super-resolution has been achieved in the WO_x and ZnO mask layer super-RENS, and the field of super-RENS technology has been broadened. However, the mechanisms of such technologies are not yet fully clear, and updated achievements have been rarely reported recently.

3 Conclusions

Super-RENS technology is an excellent scheme for reducing the spot size and realizing below-diffraction-limited effect through designing appropriate film structures and using nonlinear characteristics, which can be expected to achieve ultra-high capacity data storage. The technology has the advantages of compatibility with the current optical technology, good maneuverability, and practicability. This technology has made great strides in the past decades. Various types of super-RENS were briefly summarized in this review. The AgO_x type can obtain a high resolution, but the decomposition temperature is low and the stress in the structure that originates from the deformation leads to instability. The recently proposed Ag-Si nanocomposite and silver-nanoparticle-embedded types possess enhanced localized near-field, and no deformation occurs in the procedure, which may provide an appropriate approach for long-life super-resolution optical discs. The bubble type has a higher resolution and stability than the light scattering center-type, and the obtained CNRs are close to the commercial standards. However, the deformation produced in the recording procedure and the stress generated in the structure will affect the service life of the devices. Another disadvantage of this type is its use of a high-priced rare metal. It is thought that the bubble-type is suitable to be used as the write once optical disc based on their features. Combined with the saturable absorption and reverse saturable absorption thin films, the read-only and recordable aperture-type super-RENS discs can be realized. The most significant advantage of this type is that no deformation is generated in the recording and readout procedure, that is, excellent stability can be expected. This type may therefore be the best among the candidates for practical applications. Current research suggests that the capacity can reach up to 100 GB per layer with a recording size of 50 nm and a radial track period of 240 nm through the use of super-RENS technology in a blue laser system. Along with the reduced mark size and track period, the storage capacity dramatically increases relative to that of the current Blu-ray disc. However, the technology is also beset by problems that are yet to be solved, such as complicated film structures, a readout power higher than those of conventional discs, and a relatively low write/read speed as a result of the existing single-channel serial signal transfer mechanisms, which restrict the practical process. Therefore, discovering appropriate mask layers, optimizing the film structure, reducing the writeread laser power, and improving the storage stability and the write/read speed can result in a super-RENS that is applicable in ultra-high density optical storage, nano-lithography, and nano-imaging technology in the near future.

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