

# Progress of super-resolution near-field structure in near-field optical storage technology

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**Abstract** Super-resolution near-field structure (Super-RENS) is one of the most promising near-field optical recording schemes with significant application prospects. The development of Super-RENS from the basic type to the third-generation is introduced. The development of mask material and the application of Super-RENS in different recording systems are summarized.

**Keywords** super-resolution near-field structure (Super-RENS), mask material, third-generation Super-RENS, recording system

## 1 Introduction

The rapidly developing digital information era has made it necessary to process and store large sums of data, audio and video information such as sounds, figures and images that require information storage technology of high density, large capacity, high speed and low cost. With 20 years of development, optical storage technology, represented by the optical disk, has become widely used in the multimedia area. However, since conventional optical disk storage is of far-field recording, enhancement of the recording density is restricted by the Rayleigh diffraction limit [1] (i.e., the maximum resolution cannot exceed  $1/2$  of the incident wave length,  $\lambda/2$ ), which makes it imperative to seek a new principle and technology to achieve ultrahigh-density optical storage. In 1992, Betzig et al. succeeded in utilizing near-field optical microscopy technology in optical storage at Bell Laboratory. They used a near-field scanning optical microscope (NSOM) in obtaining 60 nm recording domains in the magneto-optical medium, and attained an ultrahigh recording density of about 45 Gbit/inch<sup>2</sup> [2]. Since then, near-field optical storage technology has become a hot subject inves-

tigated by scientists and the industrial field. At present, available near-field storage techniques mainly include NSOM, solid immersion lens (SIL) and super-resolution near-field structure (Super-RENS).

Although both NSOM and SIL can be used to realize ultrahigh density storage, they have obvious weaknesses. For NSOM, it is difficult to control the flying height of the fiber tip, and the high-speed rotating disk surface is prone to crush the fiber tip. Moreover, the fiber tip is of low light-passing efficiency and inclined to pollution. For SIL, it is difficult to maintain a specific distance between the reading head and the disk in the scope of a near-field. In addition, processing SIL with high reflectivity and minilength is also troublesome.

In summary, technical restrictions prevent the two techniques mentioned above from becoming marketable in a short period of time. However, the proposed Super-RENS may overcome the shortages of these two techniques, and is considered to be one of the most promising ultra-high density optical storage technologies that can be used in practice.

## 2 Basic styles of Super-RENS

To prevent the problem of the fiber tip being crushed by the high-speed rotating disk surface, the method of regarding the fiber tip and the recording medium as a whole system was proposed. In this system, the metal material surrounding the tip is placed in the medium, which is separated from the recording film by a protection layer, as a dielectric material. However, the metal must be replaced from Au or Al into another material so that an optical change caused by the change of light intensity or temperature can take place. One of the important advantages in this structure is that the space between the tip and the medium is replaced by a solid layer instead of air.

Based on the theory above, Tominaga et al. brought forward a Super-RENS disk structure, in which Sb is used as the mask layer material. With this kind of structure,

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they succeeded in obtaining recording marks with lengths of 90 nm and carrier-to-noise ratio (CNR) of over 10 dB in an optical system with laser wavelength of 686 nm and numerical aperture (NA) of 0.6 [3]. The structure of the disk, shown in Fig. 1, uses SiN/Sb/SiN as the mask interlining layer and phase change medium GeSbTe as the recording medium. When the laser is introduced into the Sb layer, Sb melts immediately due to the high energy in the spot center. Since light-passing efficiency of the amorphous Sb is much higher than that of the crystalline Sb, a hole forms in the Sb layer with a diameter less than that of the laser spot [4]. When the laser is withdrawn, the melted Sb crystallizes to recover. The response time for the transition of Sb between the crystalline and the amorphous state is less than 1  $\mu$ s, and the process is reversible. In the near-field area, the spot diameter is decided by the size of the aperture instead of the laser wavelength, and thus the super resolution is realized. This type of Super-RENS is called transmitted-aperture super-resolution near-field structure (TA-Super-RENS).

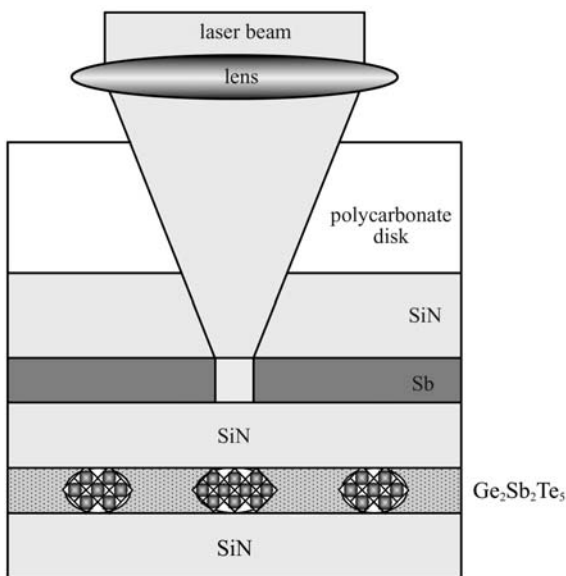


Fig. 1 Aperture style Super-RENS

Tominaga et al. advanced another mask material  $\text{AgO}_x$  [5] in 1999, with  $\text{ZnS-SiO}_2$  as the dielectric layer. In this experiment, a CNR of no less than 30 dB was obtained from recording marks of 200 nm, and the structure is shown in Fig. 2. When the laser is introduced into the  $\text{AgO}_x$  layer, the center temperature rises to 160°C, and  $\text{AgO}_x$  begins to be decomposed into Ag and  $\text{O}_2$  nanoparticles. The strong compressive surface plasma effect emerges when the Ag nanoparticles are irradiated by the laser. The compressive stress phenomenon thus happens in the center of the focused laser spot, which makes the super-resolution writing and reading achieved on the recording layer. When the laser is withdrawn, Ag and  $\text{O}_2$  combine to produce  $\text{AgO}_x$  – this style of Super-RENS is called light-scattering

center Super-RENS (LSC-Super-RENS). Although resolution of the TA-Super-RENS is higher than that of the LSC-Super-RENS, the latter attracts more scientists because the signal intensity can be increased.

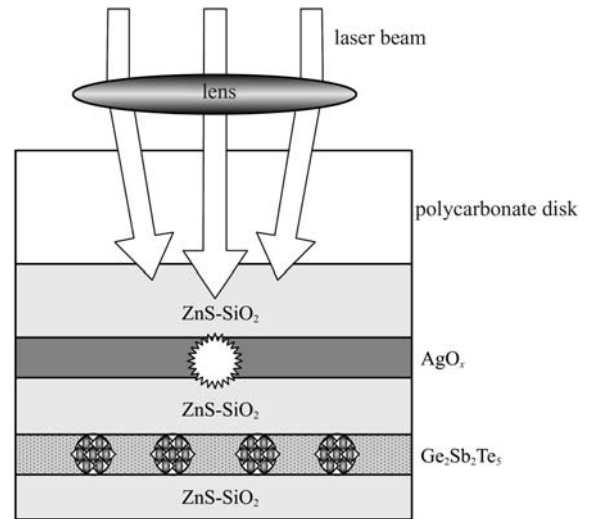


Fig. 2 Scattering center style Super-RENS

The weakness for LSC-Super-RENS is that it restricts enhancement of the disk property. The decomposition temperature of the mask layer (160°C–200°C) is close to the phase change temperature of the recording layer  $\text{GeSbTe}$  (about 160°C). Thus, it is not stable for recording marks in the readout process. By doping adequate Ag or O in the recording layer, the phase change temperature can be improved to 200°C [6,7]. In addition, the doping of a small precious metal, including Pt, Pd and Au, can not only improve the thermal stability, but also increase the decomposition temperature of  $\text{AgO}_x$  (about 200°C–300°C) [8]. To improve the CNR of LSC-Super-RENS, as well as the repetitive reading property, and to enhance the margin of readout power, scientists advanced some modified methods such as the double mask layer structure [9] shown in Fig. 3.

### 3 Research progress of Super-RENS mask material

Mask layer is significant in the Super-RENS, and its property directly affects the writing/reading speed of the optical disk, the stability of the readout signal and the CNR. Thus, the “aperture opening” speed of the mask material, namely the response time, should be short enough. The material should also have good thermal stability and excellent reproducibility. Besides Sb and  $\text{AgO}_x$ , scientists have advanced other mask materials.

The conventional Super-RENS has weak thermal stability. Thus, when the readout power increases at the

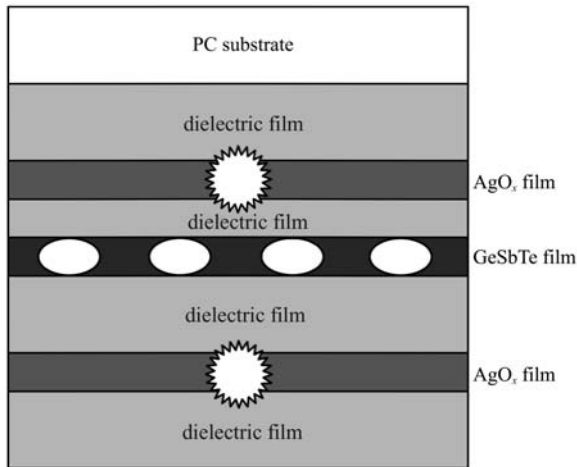


Fig. 3 Super-RENS with two  $AgO_x$  layers

opening threshold value, jitter becomes prominent. To solve the problem, Shi et al. suggested that  $Sb_2Te_3$  could be used as the mask material [10]. They also advanced a new structure with an additional thermal protection layer. The new layer, separated by the dielectric layer, is sandwiched between the mask layer and the phase change layer. Compared with the Sb mask, it was found that the new structure had much less jitter, the thermal stability was largely improved, and recording marks of 56 nm were obtained. Based on these capabilities, they advanced two structures, both of which have a localized surface plasmon coupling layer (LSPCL) [11]: polycarbonate substrate/ $ZnS-SiO_2$  (100 nm)/ $Sb_2Te_3$  (10 nm)/ $ZnS-SiO_2$  (10 nm)/LSPCL (10 nm)/ $ZnS-SiO_2$  (50 nm)/GeSbTe (10 nm)/ $ZnS-SiO_2$  (20 nm); and polycarbonate substrate/ $ZnS-SiO_2$  (100 nm)/LSPCL (10 nm)/ $ZnS-SiO_2$  (10 nm)/ $Sb_2Te_3$  (10 nm)/ $ZnS-SiO_2$  (50 nm)/GeSbTe (10 nm)/ $ZnS-SiO_2$  (20 nm). Not only can these new structures reduce the lengths of recording marks, but also improve CNR. Compared to  $Sb_2Te_3$  type Super-RENS without LSPCL, the modified versions have recording marks with

smaller lengths at 31 and 36 nm, respectively. With the readout power between 4.0 to 6.5 mW, the CNR of 25 dB, 5 dB higher than that of the conventional  $Sb_2Te_3$  Super-RENS without LSPCL, was obtained from recording marks of 103 nm. In 2004, they further advanced that  $Sb_{70}Te_{30}$  could be used as the mask material, and recording marks with minimum length of 62 nm was obtained [12]. The structures are shown in Fig. 4.

In 2002, Lin et al. advanced a new Super-RENS: polycarbonate substrate/ $ZnS-SiO_2$ / $ZnO_x$ / $ZnS-SiO_2$ /Ge $_2$ Sb $_2$ Te $_5$ / $ZnS-SiO_2$  [13]. With the readout power of 5 mW, the CNR of recording marks of 100 nm surpassed 33 dB. In 2003, Kim et al. reported that Super-RENS with  $WO_x$  used as the mask layer could have higher transition temperature and better thermal stability compared to  $AgO_x$  [14]. In addition, some other experiments reported that Bi could also be used as the mask material [15] and had similar properties with Sb type Super-RENS.

### 4 Third-generation Super-RENS

In 2002, Kikukawa et al. reported that the optical system with laser wavelength of 635 nm, lens NA of 0.6 and recording marks with lengths of 200 nm, could have a CNR over 46.1 dB in the Super-RENS with  $PtO_2$  as the mask material, even a CNR over 42.3 dB could be derived from recording marks with lengths of 150 nm [16]. Moreover, the CNRs of the recording marks with lengths of 200 nm had no changes after running through readout processes 30000 times. A Super-RENS structure with  $PdO_x$  as the mask material was advanced in 2003, and CNRs of 37 and 41 dB were obtained for the recording mark lengths of 100 and 150 nm, respectively. The mechanisms of the two Super-RENS structure mask materials were extremely similar, both of which were called the third-generation Super-RENS. A typical third-generation Super-RENS is shown in Fig. 5. When the laser is introduced into the disk, bubbles which contain

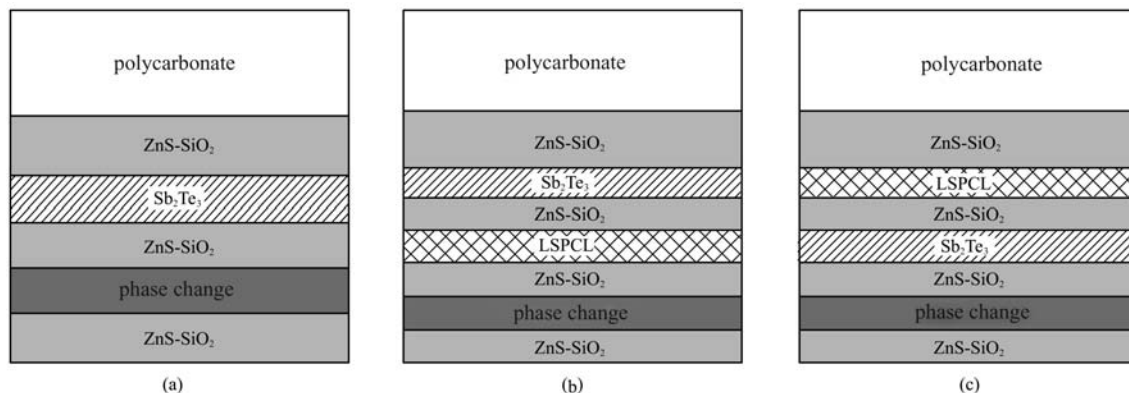
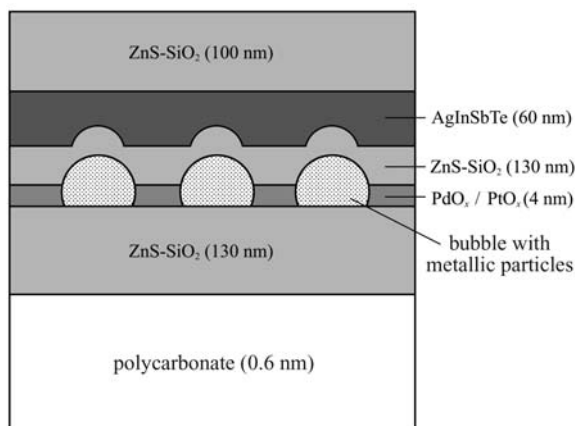


Fig. 4 (a)  $Sb_2Te_3$  type Super-RENS disk; (b) Super-RENS with LSPCL behind the mask layer; (c) Super-RENS with LSPCL in front of the mask layer

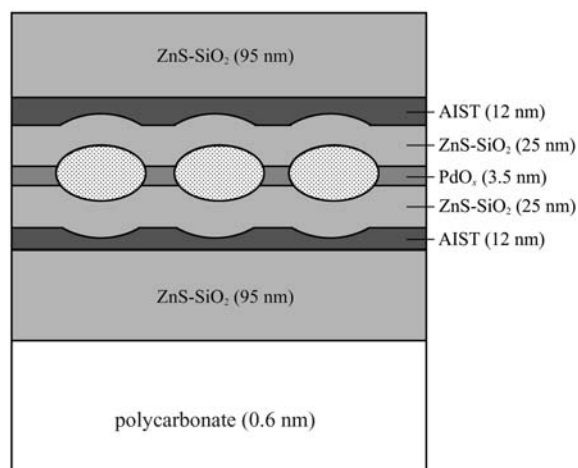
metal nanoparticles and  $O_2$  are produced due to the thermal decomposition of  $PdO_x/PtO_x$ . In addition, the AgInSbTe (AIST) layer used as the optical recording material begins to have the phase change and deformation similar to the situation in  $AgO_x$  type Super-RENS. The distinction is that bubbles produced by the decomposition of  $PdO_x/PtO_x$  are strictly separated, but metal nanoparticles in the bubbles are finer.



**Fig. 5** The third-generation Super-RENS with a semi-circle structure

In 2003, Kim et al. reported an elliptical bubble-type Super-RENS with a symmetrical structure of two AgInSbTe layers [17] shown in Fig. 6. Ductile AgInSbTe layers were deformed by elliptical volume expansion which originated from the decomposition of the  $PtO_x$  layer, and the elliptical bubble was produced simultaneously. This type of configuration, different from the conventional semi-circle type structure, is called elliptical bubble-type Super-RENS structure. At 3.5 mW readout power, clear wave forms with approximately 47 dB CNR were obtained. In the case of 80 nm mark length signals, a CNR of over 43 dB was obtained at the readout power of 3.5 mW in this elliptical bubble-type Super-RENS structure, while the CNRs were 30 and 10 dB respectively in the semi-circle structure with the same two mark lengths. Another distinctive feature of the elliptical type Super-RENS disk was that the CNR increased rapidly to over 30 dB, while the value for the semi-circle was constantly 0 dB at around 2 mW. Lower readout power makes the stability better. It can be predicted that this result is significantly related to the smaller Pt nanoparticles generated in case of the elliptical type compared with the conventional super-RENS. As a result, much smaller Pt nanoparticles may become more sensitive as the readout power increases.

The third-generation Super-RENS has a higher CNR and better readout stability. The elliptical bubble which contains metal nanoparticles plays an important role in the recording process. Moreover, Pt nanoparticles which



**Fig. 6** The third-generation Super-RENS with a elliptical bubble-type structure

are activated in the area of the rigid elliptical bubble scatter the light abnormally by a laser photon or a thermal effect. However, details are not clear at the moment and further work is needed to elucidate the readout mechanism.

## 5 Applications of Super-RENS in other recording systems

Since the Super-RENS structure was built up on the basis of the Super-RENS disk, the Super-RENS are mainly applied to the phase change (PC) Super-RENS disk at present. The recording medium used in such systems is a PC medium such as GeSbTe and AgInSbTe. Besides the PC recording system, scientists are trying to use Super-RENS in many other recording systems, and some fine achievements have been made.

### 5.1 Super-RENS applications in magneto-optical recording systems

Kim et al. reported a light-scattering center type Super-RENS magneto-optical (MO) disk [18]. The main structure of the disk, shown in Fig. 7, is similar to the one shown in Fig. 2, and the difference is that the magneto-optical medium TbFeCo is used as the recording layer instead of GeSbTe. The signal light-modulation intensity of the 300 nm marks, recorded by a 680 nm laser and a lens with an NA of 0.55, was amplified 100 times compared to the conventional MO media. The transparent aperture produced by the Sb mask layer cannot conserve Kerr polarization, but a light-scattering center which generates from the  $AgO_x$  decomposition can. Resolution of less than 200 nm was achieved because  $AgO_x$  can enhance the MO signal according to the surface plasma effect, which breaks through the diffraction limit.

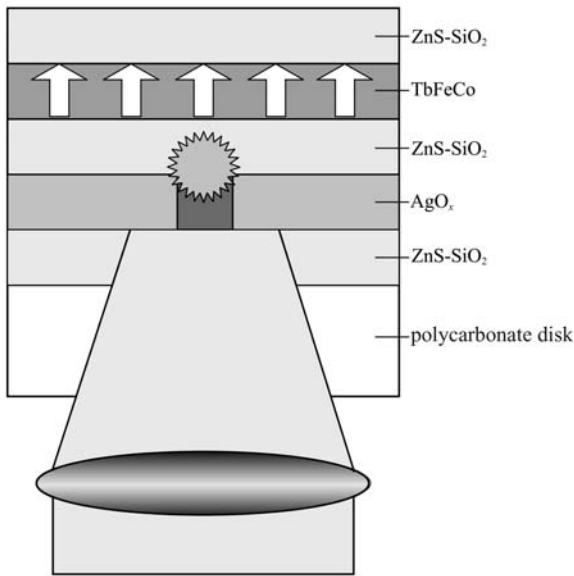


Fig. 7 Light-scattering center type Super-RENS magneto-optical disk

## 5.2 Super-RENS applications in reactive diffusion recording systems

The recording mechanism of MO data storage is the magnetization reversal by the external magnetic field and the laser heat, namely heat-assisted magnetic recording (HAMR), which results in magnetic Kerr and Faraday rotation of the incident light. In contrast, in the PC recording, the recording layer may change between the amorphous and crystalline state due to laser heating, which varies the reflective index. Reactive diffusion recording research, including recording and retrieving signals, reported by Kim et al. [19] were conducted in both MO and PC drive with the same disk.

The recording medium used in the reactive diffusion recording is the rare-earth transition metal (RE-TM), which is the typical MO material. The disk is of light scattering center type super-RENS structure, but the films are slightly thicker than the original structure. When heated, the reaction of the recording medium and the neighboring dielectric layer begins to include both sulfuration and oxidation of the RE-TM (mainly sulfuration). The RE-TM thin film is thus crystallized and reacted, which leads to changes in the optical constants, reflectivity and volume expansion. Thus, the reactive recording not only has properties of MO recording, but also properties of PC recording. Experiments showed that for 100 nm-mark length signals, the CNR of the conventional PC Super-RENS disk was 12 dB, the decomposition temperature of the mask layer (about 433 K) is close to the transition temperature (about 453 K) of the recording layer, and the readout power is about 3.0 mW. However, the CNR

(24 dB) of the sample disk of RE-TM reactive recording is twice as high as that of the PC super-RENS disk. The reaction temperature of the recording layer is above 573 K, and the readout power margin is higher than 3.3 mW. Experiments of reading and writing with blue laser (wavelength of 405 nm) showed that reflectivity of the RE-TM layer has changed significantly, which means that the sample disks could be set in the blue laser drive system as well as the red drive system, and a better CNR could be expected. Nevertheless, details of the reactive recording are not yet clear, so further research is needed.

## 5.3 Super-RENS applications in blue laser systems

Based on the Rayleigh criterion, the diffraction limit of conventional optical storage can be calculated by  $\Delta x = 0.61\lambda/NA$ , giving two ways to compress the spot and improve resolution. One way is to shorten the wavelength of the incident light; the other is to increase the numerical aperture. The application of a blue laser achieves the goal just by these two ways. Compared to the red laser (wavelength of about 650 nm, NA of about 0.6), the blue laser has better resolution with wavelength of about 405 nm and NA of about 0.85. However, since the application of blue laser technology to improve the optical storage density has been close to its limit, other technologies need to be associated with the blue laser and explore its potential. The emergence of the Super-RENS provides new opportunities for the development of blue laser technology.

In 2002, Hsu et al. proposed an inorganic write-once recording material  $SbN_x$  (antimony nitride) for Super-RENS disks [20]. The layer structure is polycarbonate substrate (0.6 nm)/ZnS-SiO<sub>2</sub> (170 nm)/AgO<sub>x</sub> (15 nm)/ZnS-SiO<sub>2</sub> (40 nm)/ $SbN_x$  (25 nm)/Ag (100 nm)/UV-curing resin/dummy PC substrate (0.6 nm). The CNR of the 150 nm mark length was about 44.2 dB at a readout power of 2.5 mW using blue laser. A below-diffraction-limited mark length as short as 60 nm was read out by using a 405 nm blue laser with a lens of a 0.65 NA.

The combination of PdO<sub>x</sub>/PtO<sub>x</sub> type Super-RENS and the blue laser system is also a hot subject. The third-generation Super-RENS has a higher CNR (over 40 dB) than the conventional structures, but its mark length is in the range of 100–200 nm. If combined with blue laser technology, the resolution can be further improved. In 2004, Kim et al. obtained a CNR of 43 dB from recording marks of 75 nm using a 405 nm laser with a lens of a 0.85 NA in the third-generation Super-RENS PC disk [21]. Based on these results, the CNR could also be improved by fabricating an Ag-nanostructured film on the top dielectric layer [22]. As illustrated in Fig. 8, the thickness  $d$  of the top dielectric layer (top ZnS-SiO<sub>2</sub> layer) was varied from 5

to 120 nm as the experimental parameter, and the CNR for 100 nm mark signals was significantly improved by applying such an Ag-nanostructured film by using a 405 nm wavelength laser and a 0.65 NA lens system.

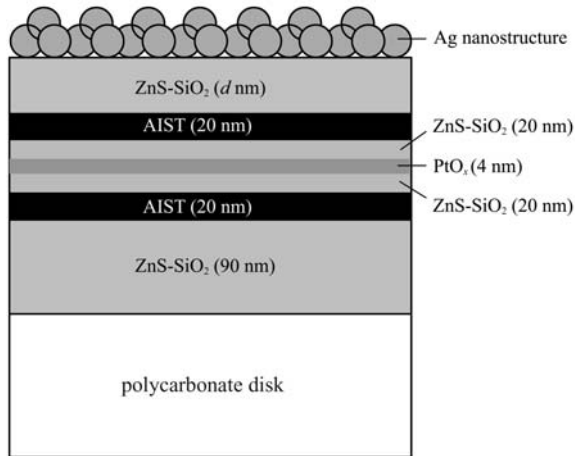


Fig. 8 Super-RENS with Ag-nanostructured film

## 6 Conclusion

Since the theory of super-resolution near-field started becoming more advanced, it has attracted much attention from scientists. It is the most promising storage technology that can be taken to applications at present. Some institutes and corporations, including the Institute of Material Science and Engineering in Taiwan University in China, Shanghai Institute of Optics and Fine Mechanics in China, AIST (National Institute of Advanced Industrial Science and Technology) in Japan, DSI (Data Storage Institute) in Singapore, Department of Precise Instruments and Mechanicals in Tsinghua University in China, Sharp, TDK and Samsung are dedicating research to the super-resolution near-field. It has taken only several years for Super-RENS to develop from the Sb type to the AgO<sub>x</sub> type and the third-generation type, which shows significantly fast development. Super-RENS can be used not only in the optical storage area, but also in many other fields that include photoetching [23]. Although the mechanisms of Super-RENS are not completely clear at present, many scientists are still interested in them. Since Super-RENS has built a solid foundation for Terabyte capacity storage, it is believed that it will play an important role in promising ultra-high density optical storage technologies with major application prospects.

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