New Optical Disk System of Ultrahigh Density and High Data Rate Using 2-D VCSEL Array

<Nano-fabrication for Evanescent Light Enhancement by Surface Plasmon Polariton>

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ABSTRACT

Higher density optical disk system of super parallel optical heads using a two dimensional VCSEL array are described for the higher data transfer rate and technological capability. Optical heads of the VCSEL array and microlens array play a key role to get higher evanescent light from a small aperture for the optical disk system, of which disk surface is coated with a lubricant and protective film on the flat recording medium in order to keep the gap between the super-parallel optical head and the disk surface within 20 nm. Higher throughput efficiency has been obtained in the near-field semiconductor optical probe array head. However, the obtained evanescent light power is about 10μW from the 100nm probe aperture using a VCSEL 1mW laser output power, which is still not enough to write bits on the phase change optical disk medium. One solution for improvement of the writing power is to develop a special nano-fabricated corrugated thin metal film for higher throughput efficiency by surface plasmon polariton enhancement. A metal fine grating fabrication method to get evanescent light wave resonantly enhancement has been studied with a FDTD simulation result.

Keyword: optical data storage, micro optics, near-field optics, nano-fabrication, micro-lens, FTDT simulation, surface plasmon polariton, contact head, optical disk, surface recording, VCSEL array

1. INTRODUCTION

In recent years, it is required to realize the ultra-high density optical memory for the new trends of digital applications for moving pictures and the rapid increase of data capacity in personal computers. Among many approaches to increase the data capacity in the optical data storage, near-field optical system has been considered as one of candidates for next generation data storages.[1-3] However, optical power of an evanescent wave at the nano-aperture is very weak due to the cutoff wavelength and low optical throughput of the probe, resulting in many difficulties to apply it to the real optical data storage. To improve the optical efficiency of nano-aperture probe and realize fast data transfer rate, the parallel optical array head has been proposed and prepared using a VCSEL (Vertical Cavity Surface Emitting Laser[4]) array and a flat-tip microprobe array.[5-11] Since the 2-dimensional array system is based on the multi-beam recording with a small spot size with an aid of high efficiency microprobe design, it has advantages for both approaches of fast data transfer rate and high memory capacity[2,3]. Figure 1-3 show the schematic diagram of 2-dimentional array recording system and the integrated head structure. As shown in Fig. 3, the VCSEL array is inclined at a specific angle (for example, 0.57˚ for 100x100 array head) to the track direction to align all light sources on separate data tracks. In this array head, all lasers are manipulated simultaneously to record the data on and read them from multi- tracks. The realization of small laser spot with sufficient power is an important requirement for increasing the memory capacity in this parallel optical system. The integrated structure of VCSEL and flat-tip microprobe arrays has also been studied to produce more compact optical array head, as shown in Fig. 1. The light from VCSEL is focused using microlens and guided to the nano-aperture of microprobe flat-tips. The optical throughput was increased with the use of semiconductor materials of high refractive index and flat-tip structure for higher intensity of laser beam at the aperture, resulting in the

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improved optical throughput of 1.25% with the 150 nm aperture in the GaP semiconductor microprobes.[10,15)]

However, it is not enough to record the 150 nm or less marks on the conventional phase change optical media because the near-field optical power from 1 mW single mode VCSEL is only 12.5 μW with a 150 nm aperture in the experiment.[10,15)] Thus, the enhancement design of optical throughput in the nano-aperture head is still required for the near-field optical data storages and other near-field applications. There are some efforts to enhance the near-field optical throughput for the nano-apertures of near-field applications, including metal structure modifications and propagation mode control methods.[11-15)] From the finite-difference time-domain (FDTD) simulation, the optical throughput was improved with the buried type microprobe with asymmetric metal-coated structure since it is a better structure for the coupling efficiency between propagating wave and surface plasmon polarition.[15)] The 'Scoop' type of metal coating on the microprobe (metal coating on just 3 side planes) also improved the light field intensity at the metal aperture and decreased the beam spot size.[8)] Theoretical calculation of high optical power throughput using the "C"-aperture design was reported with the optimization of the aperture structure design and metal thickness control to increase the resonant transmission up to ~1000 times power throughput.[11)]

In this study, we have developed new head structure using the microlens and metal film grating for the surface plasmon enhancement. The integrated optical head of VCSEL and microprobe array has been modified to increase the optical throughput with the patterned 2-dimentioal metal grating by the surface plasmon resonance effect. The FDTD numerical simulation was conducted to find the best structural design of metal grating, including the grating pitch and grating width and metal thickness. Finally, basic experimental approach will be discussed to realize the integrated array head and apply it to the real optical data storage.

2. DESGN OF THE INTEGRATED OPTICAL NEAR-FIELD PROBE

Figure 1 shows the Integrated Optical Near-field Probe consisted of the VCSEL, the high NA micro-lens and the self-aligned NF-Probe (Pyramidal Prism Probe :PPP). This figure is only one part of the Integrated Array Head. The VCSEL consists of a multi-quantum active layer and a current confinement oxide layer sandwiched by two DBR multi-layers. An Ohmic contact layer and electrode layers are formed on both n-DBR layer and p-side substrate.

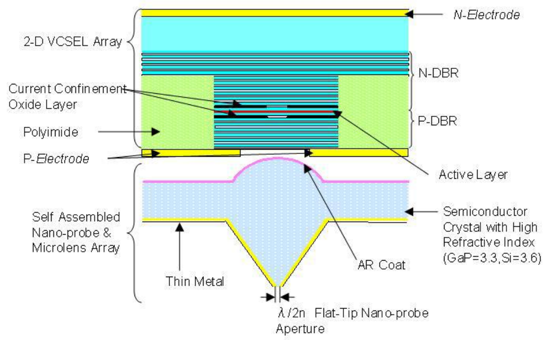

Fig.1 Only one element of the near-field optical head is shown for the schematic near-field semiconductor optical probe with high throughput consisted with VCSEL and lens.

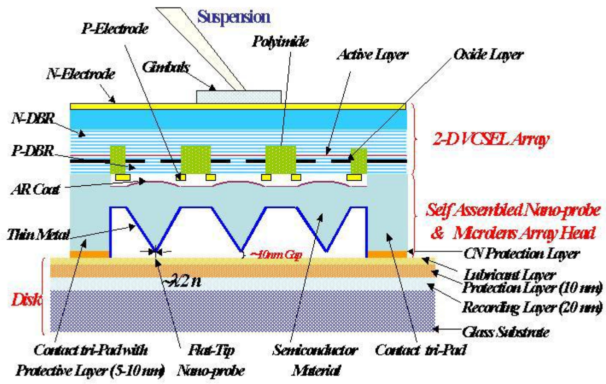

Fig.2 Cross sectional concept of the two dimensional optical array head. A part of the head is included with VCSEL, microlens and near-field probe array.

One part of our fabricated conventional near field optical disk head, in which the laser light comes from VCSEL and is focused through the microlens on the aperture of the GaP probe. With an aid of the focused light and high refractive index of GaP, the throughput of this probe is 1 % for 100nm aperture. The output window size of the VCSEL is about 8 μ meter with diameter of the one VCSEL of 10μ meter column and 25 micron meter pitch between columns as shown in Fig 2, which is only a part of the cross sectional view of the arrayed head. The total two dimensional array is schematically shown in Fig 3. The surface profile of the micro-lens in Fig. 1 is the semi-sphere which is fabricated with ion beam shower made from continuous etching mixed gas (Cl_2 + Ar) concentration during either the ion milling process or the reactive ion etching process. The each beam entrance surface of the semiconductor lens is anti-reflection coated with ECR sputtering. Most important technology of this probe array fabrication is the development of the self-alignment method[14] between the focal point of the lens and the aperture central position of the semiconductor near-field optical probe. First we must fabricate the 100x100 VCSEL array out of an epi-wafer processed in a VCSEL wafer manufacturer and the microlens array out of a thin semiconductor wafer (Si or GaP) for the combined devices of lens and probe array using the same mask of the photolithography. After completed the VCSEL array and the lens array (lens substrate is still remain plane), a special infrared sensitive photo-film material layer and a photo-lithographic resist layer are coated on the focal plane of the lens substrate (as shown in Fig.5,6). The visible VCSEL or the infrared VCSEL must emit each laser light and the each light beam focuses on the focal plane of the semiconductor plane surface. With the proper laser light exposure the infrared sensitive photo-film material turns black. After developing and fixing the IR sensitive material with the hypo liquid the UV light for the photo resist layer is exposed from bottom side of the plate. As the resolution of the infrared sensitive photo material is not small to fit the NF tip, the black size is bigger than the estimated tip aperture size of the PPP, so it is good for the self-aligned fabrication mask and such as SiO_2 mask can be formed using the conventional photo-lithography for the PPP. With the mask made of such SiO_2 combined with subtle etching technology the PPP fabrication will be down and the thin metal coating also will be down before getting rid of the SiO_2 mask completely, whose process is described in Fig.4 as a conventional PPP fabrication method.

This is the reason why all PPP heights are as exactly same as the plate thickness of both those of the lens and the PPP material. This same height feature is very important for the optical contact head where the three pads only contacts to the disk through the lubricant over the cover layer of the recording medium [3,5] and all the PPP tips are apart from the lubricant layer with about 10 nm gap. The disk rotation speed is rather slow because the contact head consists of 2500 Near-field probes (when the array consists of 50x50 elements). The roughness of the micro-lens surface is17.65 nm (rms) which is quite smooth after getting rid of the contamination deposited on the lens surface by chemical resulting out of the dust from the photo resist etching and the chlorine active gas in the RIE chamber. By the ion beam irradiation for removing the contamination using Oxygen shower after forming the microlenses array on the surface of GaP or Si as shown in Fig.8 which had been taken using AFM..

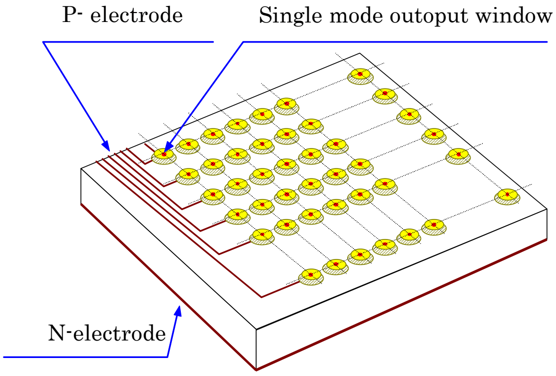

Fig. 3 Schematic figure of a 2D array super-parallel head, which is inclined to the disk tangential direction as shown in reference 1.

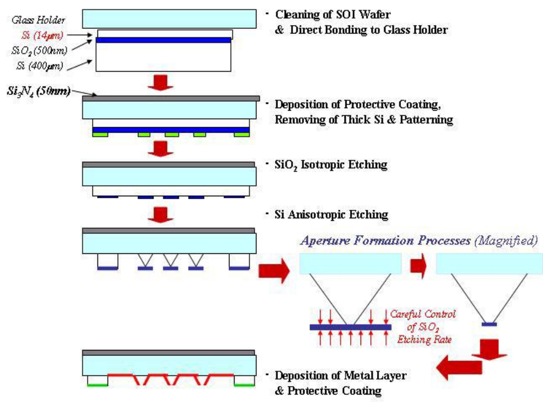

Fig. 4 Fabrication method of 2-D semiconductor near-field probe array made of Ge or GaP material and each has the same probe height

3. FABRICATION OF MICROLENS ARRAY

The micro-lens fabrication process is shown in Fig. 5 and 6. For the first step the conventional photo resist layer is formed by means of the spray coating method on the surface of the thin semiconductor substrate. Column patterning is formed by the photo lithographical method as shown in Fig.6. when the substrate heated up to about 200℃, the columns become semi-spherical shapes for the sake of surface tension. After heat treatment and being exposed in the ion beam camber the Si or GaP plate is etched and the shape of the semi-sphere is transferred to the semiconductor material. Thus the spherical curvature can be fabricated as shown in the SEM picture of Fig.7. The curvature of one of the lens array has been measured by the AFM as shown in Fig. 8. The spherical curvature can be calculated by the ray tracing method using the Smell's equation with both conditions of the exact focal point on the x-y co-ordinates and the diffraction angle of the VCSEL output with its wavelength. The calculated throughput efficiency of this probe is about 3.5 % when the aperture of the PPP is 100 nm and the refractive index of the GaP probe is 3.3 for 670 nm wavelength and the NA of the spherical lens is 0.5. This figure of 3.5 % is the case of the whole Gaussian beam of the VCSEL light, however the peak power of the evanescent light just beneath the aperture of the PPP will be extracted more than that, perhaps 10 % of the input power. The required light power from the top aperture of the PPP is about 50 u W when the aperture size is 100 nm. This means that the each VCSEL output power should be about 1.5 mW for the case of 3.5 % and can be estimated as about 0.6mW for the case of 10 % throughput. If the PPP aperture size is 30nm , then the needed light power from the PPP for the PC disk writing will be about 6µW. In this latter case the VCSEL output power will be only 60 µW when the throughput efficiency is 0.1% in this narrow aperture case, then the total VCSEL power for 50 x 50 array will be 150 mW, which will be reasonable value for the VCSEL array head.

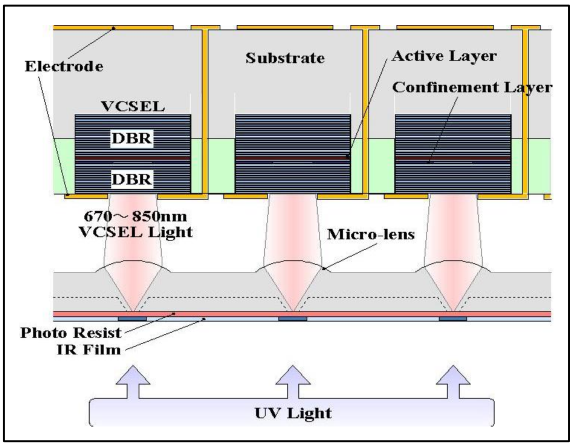

Fig. 5 Fabrication method to obtain the nano-meter controlled adjustment between focal points of each VCSEL light and each aperture of the probe array, where photo resist and IR film resin are specially used.

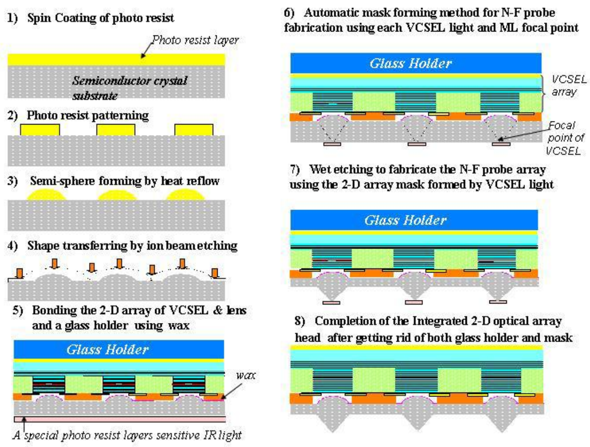

Fig. 6 Nano meter controlled 2-D microlens array and N-F probe array fabrication method using a self- alignment technology with VCSEL.

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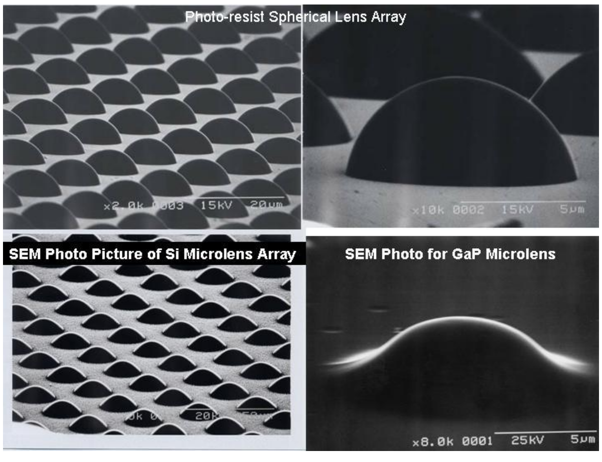

Fig.7 Upper photos show the semi-sphere resist lens array and the lower photos show the transferred semiconductor microlens array

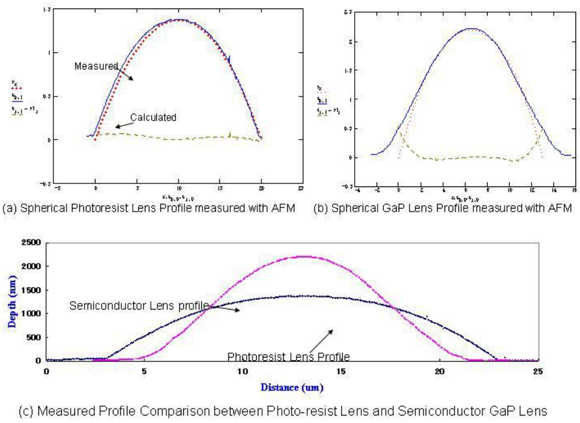

Fig. 8 Semiconductor microlens profile and photo resist lens profile measurement data using AFM. They are all spherical curves with about 10 µm diameter.

4. IMPROVEMENT FOR THE N-F PROBE THROUGHPUT

There will be more improvement for the probe throughput efficiency by applying the surface plasmon polariton effect to the probe outer surfaces with thin Au metal film coating. The surface plasmon polariton never decrease the power even if the aperture is narrower than the cut off wavelength. If there is the phase matching condition between the surface plasmon polariton wave of transversal and the light wave of longitudinal, then the power of the not decreasing surface plasmon wave will be converted into useful light wave for writing the bits on the optical disk surface.

Figure 9 shows FDTD calculation results of PPP partly covered with gold metal film. Figure 10 shows the electric field intensity of the light out of the PPP apertures for the various type of the thin metal cover.

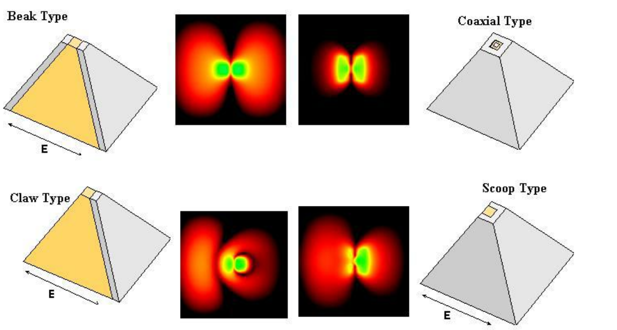

Fig.9 Various types of PPP (pyramidal prism probe) covered with metal thin film

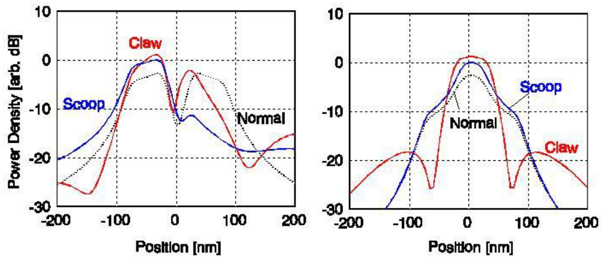

Fig. 10 Simulation result by FDTD method.. Light power density profiles out of the probe aperture are changed for various sides covered with metal film

5. ASSEMBLING VCSEL AND MICROLENS PLUS PPP

Before assembling those optical arrays into one integrated unit for the writing and reading experiments through-hole technology for electrodes to each VCSEL is needed to use the limited space between the VCSEL array and the lens /PPP array which is apart from each other with only 25 micron meter pitch. After finishing the assembling of the two optical units, that is the Micro-lens array and the NF probe array, writing and reading experiment will be performed in the near future. Figure 8 shows maximum deviation of 40 nm between calculated and measured curvatures of the micro-lens. The focal length of micro-lens prepared in this research was measured. It was found that the self-alignment between the focal position of the microlens and the exact aperture position of the Near-field optical probes can be adjusted using the self-alignment technology. The lens diameter about 10 µm shows any difference in beam waist size between spherical and aspherical microlens. Very high throughput efficiency as shown in Fig.11 had been obtained using microlens between VCSEL array and near-field semiconductor optical probe array. Figure 12 is one of the PPP array fabricated in this experiment.

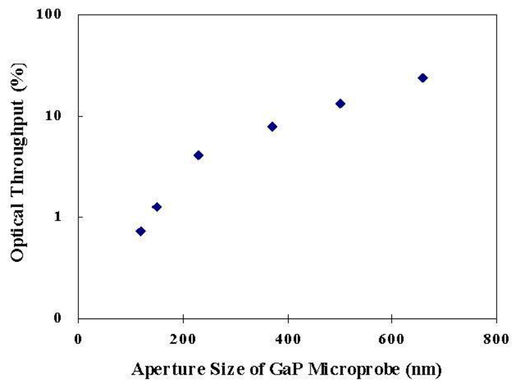

Fig. 11 Experimental result of higher throughput efficiency in the near-field semiconductor optical probe array which is shown in Fig.12.

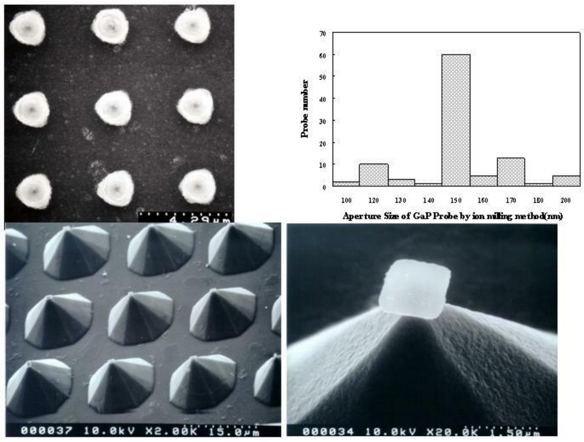

Fig.12 One of examples for the near-field optical probe array fabricated in this experiment, where is the aperture size distribution also shown.

6. NEW OPTICAL HEAD DESIGN

The head surface consists of gold grating thin film inside the GaP base materials, where a patterned width and depth of gold film are 10nm and 30nm, respectively. The other side of a GaP material also works as a microlens array to focus the VCSEL light beams on both the each aperture and the each fine grating tooth around the aperture. This type of head design requires the micro and nano-fabrication using a non-doped semiconductor and a gold metal material. The schematic diagram of optical devices with periodically corrugated gold thin film having a tiny nano aperture is shown as in Fig. 13. It is really required to improve the evanescent light throughput efficiency from a small aperture of 30 nm diameter up to 1 % to realize the evanescent light of 10μW using 1 mW VCSEL output power.

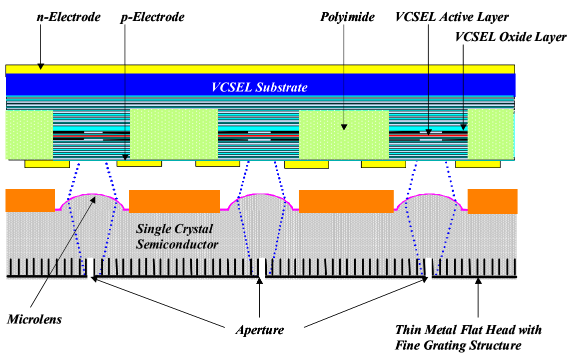

Fig.13 A flat top Near-field optical head with an aperture array and periodically corrugated Au metal thin film over a semi conductor microlens base, in which laser beams from a VCSEL array irradiated.

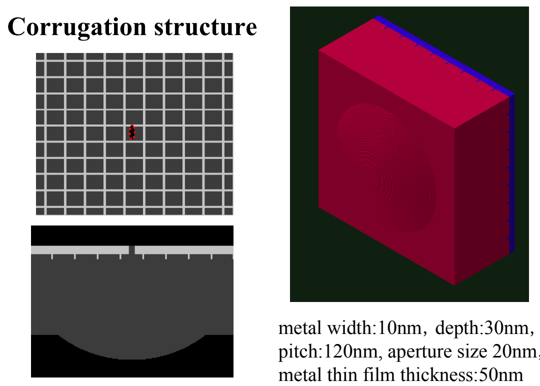

Fig.14 Schematic figure as shown in Fig.13. In this case only one element of the integrated optical head is three dimensionally shown without VCSEL. We can see the nano-aperture surrounded by fine gold grating structure.

7. NANO FABRICATION METHOD

Figure14 is a schematic figure of a part of the head which is shown in Fig.13. In this figure only one element of the integrated optical head is three dimensionally shown but the VCSEL element is not shown. We can see the nano-aperture (30nm diameter) surrounded by fine gold grating structure (corrugated gold thin film). The formation of a fine grooving pattern on the GaP substrate and the filling method of a nano metal particles into the groove have been tried using an ultrahigh resolution electron beam lithography and a selective chemical bonding method between the groove inside and the metal particles with a colloid liquid of gold particles for filling gold metals inside the nano groove of 10 nm width and 30 nm depth. Figure 15 show two SEM photos of the patterned grooves on the GaP substrate. The EB pattern is 10 nm lines and 235 nm spaces. Etching for the fine nano grooves will be performed with CF4-RIE. The microlens fabrication method is reported before [15].

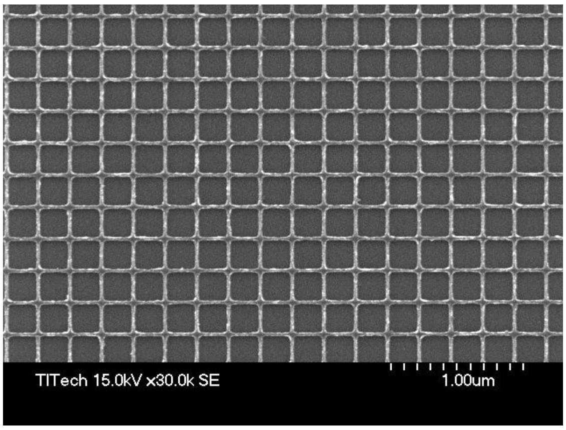

Fig.15(a) SEM observation for the lift-off patterned groves. Chromium (thickness: 30nm) had been evaporated, of which line width and spacing are 10nm and 235nm, respectively.

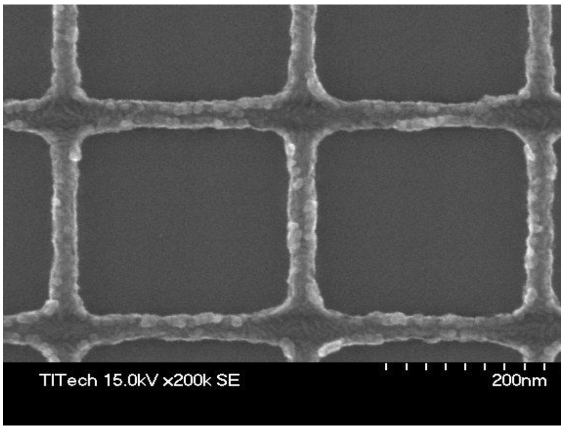

Fig15(b) Enlarged SEM observation for the lift-off patterned groves. Chromium of 30nm thickness had been evaporated, of which line width and spacing are 10nm and 235nm. However the obtained width was about 25nm

8. THE FDTD SIMULATION TO THE NEW HEAD

Ebbesen *et. al.* reported the highly unusual transmission properties of metal film perforated with a periodic array of sub-wavelength holes.[13] Though light in the visible to infrared range can not related to the surface plasmons enhancement on the metal-air interface, it is possible to couple the SPP to metal surface if a periodic structure of sub-wavelength holes is prepared on the metal film.[13,19] Thus, we tried to add the periodic structural concept on the original integrated VCSEL microprobe array head to enhance the optical throughput, as shown in Fig. 13. A periodic metal grating of sub-wavelength pitch is introduced on the bottom of semiconductor materials with the nanometer size apertures. The revised optical array head also includes VCSEL and microlens arrays so the light from VCSEL will be focused on the nano-apertures which are aligned to the center of microlens. In order to increase the optical power of the evanescent light from the super-parallel two dimensional VCSELs, the head structure consisting of the microlens and flat face aperture array with a 30nm diameter has been prepared with a thin and fine corrugated gold metal as mentioned above. Since the weak evanescent waves excite resonantly the surface plasmon polariton (SPP) waves with the fine metal corrugation, this kind of head structure is designed, where the resonant pitch of the light waves propagated inside the non-doped GaP material. All parameters are calculated using a FDTD (Finite Difference Time Domain) method.

In this study, the near-field apertures are prepared on the flat surface and thus, the focal points of the microlenses are located at the same distance. The irradiated spots in the grating plane are larger than expected focal spot size. By a

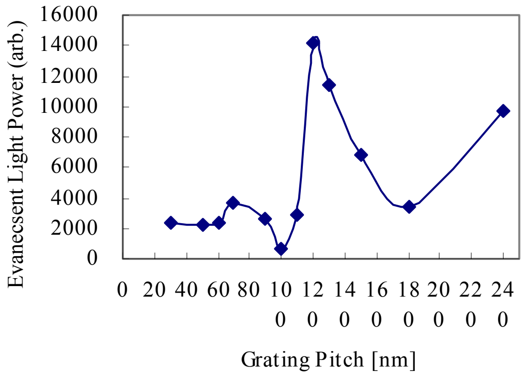

Fig.16 Resonant evanescent light power enhancement with the grating pitch of a half wavelength of the light inside the gold corrugated surface within the GaP substrate had been observed by a result of FDTD calculation. The enhanced evanescent light power ratio to the power without a resonance shows an around 500 difference.

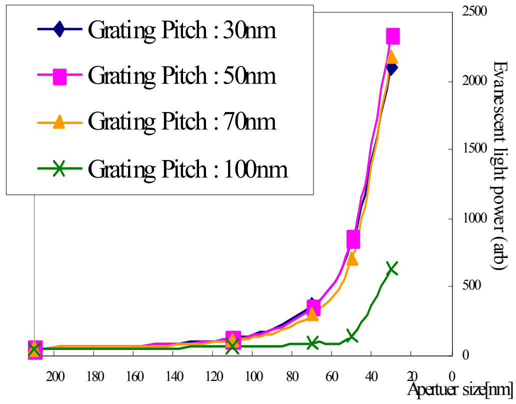

Fig.17 Calculation results of the evanescent light power vs. grating pitch variation. The power in this figure means square of the electric field of the evanescent wave.

calculation, it is observed that very high evanescent light power were enhanced resonantly when the grating pitch is coincidence with a half wavelength and the focused laser light is located inside the semiconductor head, as shown in Fig.16 and 17.

In order to obtain this resonantly enhancement result, we varied the width and depth of the fine gold metal corrugation. On the way of the calculation we found the maximum enhancement occurs when the gold metal width is about 10nm and the height is 30nm. With these parameters of width and height constant we calculated the evanescent wave electric field enhancement phenomena with the variation of aperture diameter. Figure 16 and Fig.17show some results of them. From the view point of evanescent wave enhancement in Fig.17, we understood that the smaller aperture size makes the larger evanescent light power. As for the power increment with an aid of SPP, we realized that the aperture size of the evanescent light for writing on the surface of the optical disk should be less than 30nm diameter. Figure 18 is the calculation result of the grating pitch variation with the aperture size of 30 nm diameter.

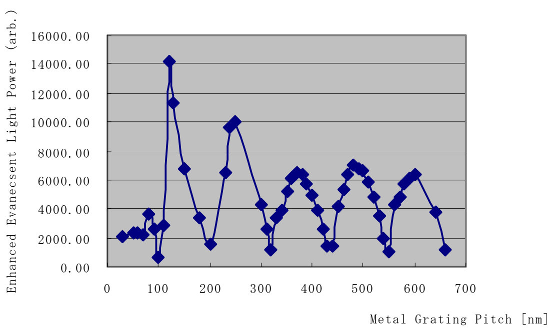

Fig.18 Calculation results of the evanescent light power vs. grating pitch variation. The power in this figure means square of the electric field of the evanescent wave.

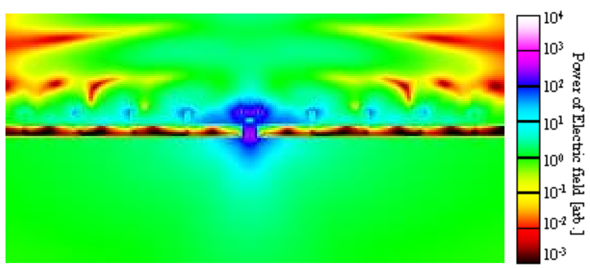

Fig.19 Even in non resonant periodicity there is a large difference between periodic grating gold surface and no periodic corrugation. In both cases the gold film thickness is only 30nm, then there we can observe leaky light field over the surface. Electric field E^2 distribution (the evanescent light wave power) near the aperture when the pitch is 118nm is observed

The wavelength is 780nm and the refractive index of GaP is 3.3. The enhanced peak evanescent light occurs when the light inside GaP is resonance with the gold grating pitches. The resonance can be seen in every half wavelength in GaP crystal. The irradiated laser light inside GaP crystal is focused around gold fine grating. Wave vector of the irradiated light and grating vector are resonance each other. From the Fig.19 we decided that the aperture surface metal thickness should be thicker than 30nm in order to prevent the leaky far-field light as shown in the figure. However the inside the aperture holes should be filled with the same material used as the substrate.

9. DISCUSSION

The interface between the gold film and the non-doped GaP crystal may support the charge density oscillations with proportion to the discontinuity of the electric field component of the evanescent wave normal to the interface. An incident electromagnetic wave excites a SPP, if the wave vector component parallel to the non-doped semiconductor and metal interface matches with the propagation vector of the SPP. Since the SPP wave vector is usually larger than the wave vector incident in a non-doped semiconductor or dielectric media adjacent to the metal film, the exciting field is usually an evanescent field produced by the grating.

In our conventional array head[5,7-8], the refractive index of the GaP is as high as 3.3 the light (780nm wavelength) beam waist size inside the semiconductor probe is almost 500 nm in diameter. Evanescent light from the 100-nm aperture on the top tip of the GaP probe is reduced to 10μW, even though the throughput efficiency is so high as 1% in our experimental case. The required light power for writing bits on the surface of the optical disk are 100μW using an 100nm aperture, and 12μW using a 30nm aperture. This means that at least 10 times evanescent light power increment for the case of 30nm aperture with the aid of the SPP is required.

The most important technology in this new head structure is that the head has the grating shape on the surface structure where the arrayed apertures are prepared by engraving the gold film surface to excite the SPP wave inside the non-doped GaP substrate. The non-doped semiconductor crystal surface covered with thin gold film, which exhibits a negative **ε** at the frequency of the incident 780 nm light shows effective SPP excitation by an incident light wave if the wave vector component parallel to the non-doped semiconductor and metal interface matches with the propagation vector of the SPP. Since the weak evanescent wave can excite the SPP waves resonantly with fine metal grating, new optical array head was designed to confirm the resonant behaviour between the input light and metal grating. The interface between the gold film and GaP substrate is related to the charge density oscillation with the electric field component of evanescent wave normal to it. This occurs at a different frequency from the bulk plasmom oscillation and is confined on the interface of metal and dielectric layer. Then only TM-polarized light can excite the SPP and the metal layer must exhibit a negative value of real part of **ε** at the frequency of incident light. Since the negative dielectric permittivity is required to support the SPP resonance, the best metal is gold or silver at the optical frequency range. An incident electromagnetic wave excites the SPP wave if the wave vector component parallel to the interface of semiconductor and metal is coincident with the propagation vector of the SPP. Since the wave vector of SPP is usually larger than that of the incident light on the semiconductor or dielectric medium adjacent to the metal layer, the excited field is an evanescent field enhanced by the metal grating. Since the surface plasmon enhancement is dependent on the polarization direction of laser beam, the evanescent field enhancement will be limited to the one direction. When the polarized direction of input light is parallel to the grating direction in the x-direction, the enhancement occurs in the grating pattern through the x-direction. However, there is little enhancement in the perpendicular grating pattern through the y-direction. Actually, our simulation results show that the surface plasmon enhancement strongly depends on the polarization direction and incident angle of focused input laser. In this research, we will use VCSEL array for light source since it has many advantages over edge emitting lasers, including the 2-dimensional array structure on the wafer, circular beam shape and single longitudinal mode. However, it shows some limitations due to the multi-transverse mode behaviour and polarization instabilities.[20] Although our system requires the polarization control of input light and the current VCSEL does not show the exact polarization control, we believe that the polarization control in VCSEL will be realized in the near future. A lot of approaches are now studied to control the polarization behaviour in VCSEL and some good results are reported by many researchers, including the growth on non-(100) substrate, design of non-cylindrical resonators, the use of polarization selective mirrors, and the method of asymmetric current injection.

10. CONCLUSION

About 500 times resonant power enhancement of the evanescent light is observed when the grating periodicity (minimum pitch is 118nm) is equal to the half wavelength of incident wavelength (780 nm) inside the GaP crystal. One of the calculated data of the evanescent light wave increment is shown. In the resonant case with the corrugated thin gold metal surface, there is larger evanescent wave enhancement compared to the case of no corrugation metal surface. It is a very interesting results that enormous power enhancement can be observed with every half wavelength in the non-doped GaP crystal. After establishment of fine engraved metal periodical corrugation with nano-fabrication and assembling the new flat type head will be developed in near future using the corrugated gold metal film on the top of the super-parallel near-field optical head as shown in Fig.13. The parallel optical array head has advantages for realizing both fast data transfer rate and high data capacity since it is based on a multi-beam recording and a small spot size using the VCSEL and microlens arrays. Since the VCSEL microprobe array head reported in the previous paper does not satisfy the required recording power for conventional phase change optical media, we have studied new structure of parallel optical array head. New structure was designed to enhance the optical throughput using the surface palsmon resonance between the incident light and metal grating. The theoretical analysis and fabrication process for new integrated array head are discussed with the emphasis on the FDTD simulation about metal grating structure. Currently we are attempting to develop new integrated VCSEL array head and evaluate the optical properties for realizing the parallel near-field optical data storage. After the establishment of fine engraved metal periodic grating with nano-fabrication process, new head will be completed with the attachment process to VCSEL array. The evanescent light power enhancement between the incident light and metal grating will be a guideline for the future near-field optical data storage application.

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