Review report of

Microlens and Micro-Wedge Optical Concentrator Technology for Solid State Image Sensor

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ABSTRACT

Microlens technology for solid state image sensor has been studied in the report. Though microlens can increase the effective aperture ratio, a reflection effect induced by the microlenses would increase optical cross talk and noise level. For high quality imaging, a new technology of micro-wedge optical concentrators (μ-WOC), is more suitable.

1. Introduction

A continuous trend of image sensors is to reduce the size. The weight of charge-coupled-device (CCD) camcorder is now less than 0.7 kg, and newly developed active pixel sensor (APS) can build a camera with size less than a 3.5 mm^3, which is about the size of a dice[1].

Photosensitivity is one of the most important characteristics for image sensors. For basic design concept, the aperture ratio (the ratio of the light-sensitive area of a pixel to the total area of that pixel) of a frame-transfer pixel is relatively high because almost the entire pixel is sensitive to light. In contrast to frame-transfer imagers, the aperture ratio of a (frame-) interline-transfer pixel is quite low. For example, near each light sensitive pixel a CCD cell of the vertical shift register is incorporated which takes up silicon space but is not light-sensitive. Typical values for the aperture ratio are between 25% to 45% for interline sensors dedicated to consumer applications. Active pixel sensor (APS) faces the similar situation, the photo-active area usually only occupies a small portion of each pixel (the typical fill factor is only about 30%), because the readout circuits and connection lines have to be built. This problem becomes more serious for small image devices, since the pixel size is only about or less than 10 μm. Three technologies have been proposed to increase photosensitivity, the photoconversion top layer technology, the microlense technology, and the micro-wedge optical concentrator (μ-WOC) technology. The photoconversion top layer technology increases the aperture ratio by depositing an α-Si photoconversion layer on top of the imager. The photoconversion layer completely covers the image section of the sensor, the aperture ratio can be increased to near 100%. However this approach brings about undesirable image lag and dark current, so such structure cannot offer high photosensitivity without deterioration in the image sensor characteristics[2].

This report discusses the microlens and μ-WOC technology and their application of image sensors. Both of the two technologies can greatly enhance aperture ratio without raising dark current and image lag; microlenses can increase the aperture ratio to near 70%, and μ-WOC can increase the aperture ratio to close to 100%. Microlenses have been used in some consumer electronic cameras, but optic cross talk and optic noise induced by microlenses may limit applying microlenses for high quality imaging. On the other hand, a new technology of μ-WOC, which is invented and under development in Jet Propulsion Lab, is more suitable for high quality image sensors.

2. Microlenses for image sensors

Microlenses have been with us for a long time. Many early lenses, including those made by Hook in the 17 century and by Leeuwenhoek in the 18th were small and resembled lentils. Many of the applications for arrays of microlenses has also been well established.

In recent years there has been a growing interest in the study of arrays of very small lenses for wide variety of applications, such as non-Gaussian imaging[3], optical fiber connectors[4], light modulators[5], display devices[6], diode laser beam improvement[7], integral photography[8], optical computing[9], and detector arrays[10]. This is due to, on the one hand several methods have been developed for making arrays that are of better quality than those that were previously available and this justifies looking again to see what might now be achieved in some of the earlier applications; on the other hand, developments particularly in optoelectronics, have miniaturization and the use of arrays of devices fabricated on a single substrate.

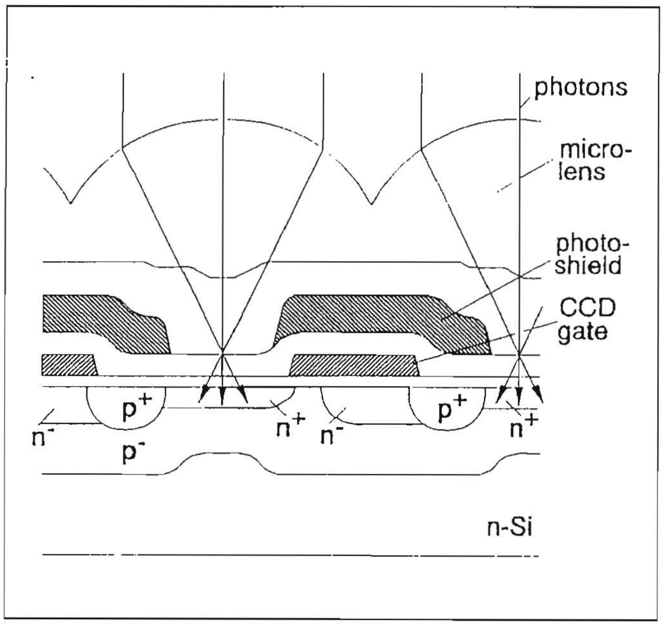

FIGURE .1. Cross section of an IL or FIT image cell provided with on-chip microlenses.

By using the focusing properties of microlens, one can confine light in a small region of a pixel, and the fill factor of pixeled image devices will increase. For example, H. Chase, et al. have reported that the fill factor of spatial modulator can be increased form 1.9% to near 100% by using microlenses. Microlenses have also been used on pixels of CCD image sensors to increase the light collecting efficiency as shown in Fig. 1. In the complete two-dimensional matrix of photodiodes each single pixel has its own microlens, consisting a based-resin layer. This means that part of the light impinging on top of the vertical CCD shift register can also be focused on the light sensitive part of the pixel. It has been reported that microlenses can increase the effective aperture ratio from 27% to 68% for unit cell size of 7.5x9.6 μm[11].

1) Microlens fabrication

A variety of manufacturing techniques have been proposed. Graded index lenses in rod or planar form have been comprehensively reviewed by Iga, Kokubun and Olikawa[12]. Cowan[13] suggested simply recording interference fringes in photoresist and various authors have considered the use of Fresnel zone plates[14,15,16]. There is also considerable interest in the manufacture of arrays of thick holograms[17,18].However, one of the simplest and perhaps most elegant techniques was described by Propovic, Sprague and Connell[19] who produced cylindrical islands of photoresist using standard photolithographic techniques and then melted them so then surface tension caused them to take up a hemispherical form. This technology had been used by Sano et al.[20] to produce various shape of microlenses on IT (interline transfer)-CCD image sensor. The fabrication process, which consists of planarization, photolitherography, lens layer pattering, and rounding off of the resin for the submicron-spaced lens array, is shown in Fig. 2. The surface of the filter layer is planarizationed by transparent plate resin as shown in Fig. 2-a. This planarization process is important in order to obtain a uniform lens array. A good planarization can be reached by adopting the multi-spin-coat process and by baking this layer on hot plates. To obtain submicron-spaced lens array, the lens resin layer, phenol resin posi-type submicron-resist, has been spin coated on the planarization layer. Then the lens resin layer has been patterned by the photolithographic process using a g-line (436 nm) submicron stepper as in Fig 2-b. The patterned lens resin (Fig. 2-c) is then melted by heating the substrate, for which the temperature is kept at a given accurate constant. As a result of rounding off the patterned resin angle, the array of submicron-space microlenses are formed by surface tension. (Fig. 2-d). Because the pixel areas are usually square or rectangular shaped, the microlenses are expected to be square or rectangular to cover the whole pixel area.

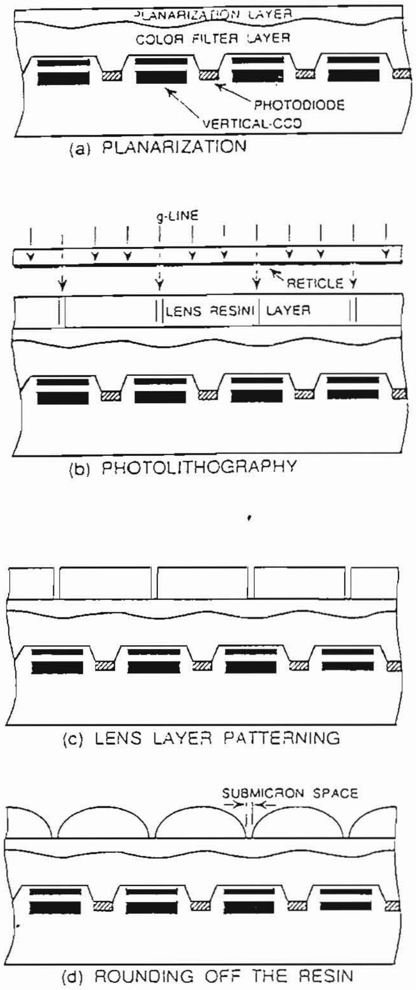

Fig. 2 Fabrication process for the submicron-spaced lens array.

For the melting process, the shape of microlenses is difficult to control. The profiles of the resist before and after melting had been measured by Daly et al.[21] and is shown in Fig.3. The process of transferring a rectangular cross-section to a circular one under the action of surface tension works reasonable well provided that the resist is sufficiently thick. Where the cross-section has a particularly low aspect ratio (the height to width ratio) the melting process merely rounds the edges but does not produce an overall circular shape. This is not helped by the action of gravity of by softening the resist in an atmosphere of solvent. When a longer focal length is required, corresponding to a shallower cap of a sphere, the surface tension of the softened resist is not sufficient to draw the material into the desired shape. This then sets a lower limit of about 0.25 on the numerical aperture of lens that it is possible to make (i.e. f/2). In other words, it is possible to make lenses of short focal length (thick lenses) but not of long focal length (thin lenses). The shape of microlenses also depends on the shape of pixels. For example, if the pixels are square or rectangular, then

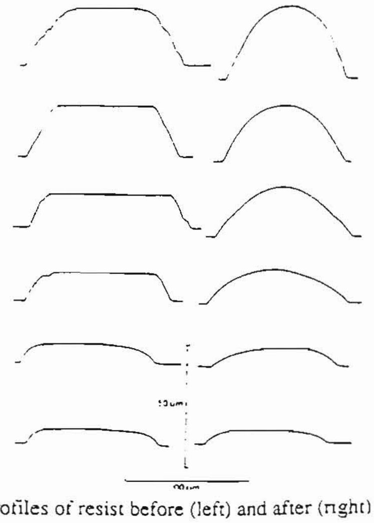

Figure 3. Profiles of resist before (left) and after (right) melting.

the microlensese are pin-cushion in shape as shown in Fig. 4.

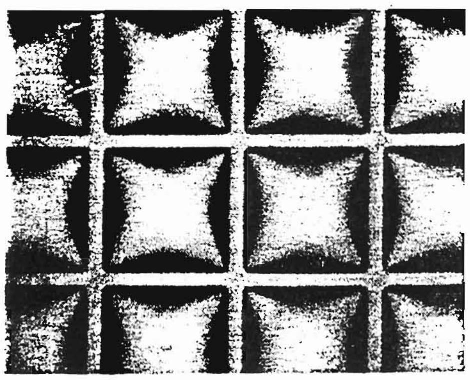

Fig. 4. For square pixel, microlenses are pin-cushion in shaped.

2) Effective aperture ratio using microlens

The effective aperture ratio can be defined as the ratio of the sum of all light beams on the unit pixel area to the sum of light beam on the photo-active area. There are two major factors for determining the effective aperture ratio: the shape of the microlens, and the focal length of the microlens.

To achieve higher aperture ratio, every microlens is expected to cover the whole pixel area which is a square or a rectangular dome. For example, if the pixel has the size of 7.5x9.6 μm and the spacing between microlenses is 0.8 μm, then the ideal maximum aperture ratio for hemispherical lens (which has a full circular structure) is only 49%, because the lens can only cover a fraction of the pixel area as shown in Fig. 5-a; for a semicylindrical lens structure (which is round only in one dimension), the lens can cover more area, the ideal maximum aperture ratio is 67% as shown in Fig. 5-b; and for rectangular dome-lens structure (which is differently shaped along its two orthogonal axes), it can cover almost all of the pixel area, the ideal maximum aperture ratio is 82% as shown in Fig 5-c. For rectangular dome microlenses, the individual lenses are pin-cushion in shape, but still would be adequate to concentrate light onto the photo-active areas. The real effective aperture ratio should be determined by the thickness and width of the lenses, the refractive indices for the lens resin and color filter layer, the thickness of color filter layer, the area of photo-active region, and the thickness of the metal shield. Sano et al. developed a micro-lens simulation program and calculated that the maximum effective aperture ratio of the rectangular dome-lens is 71%, and they claimed that they had achieved effective aperture ratio of 68% in experiment with melting process. The effective aperture ratio has increased 2.5 times compare with the aperture ratio of 27% without microlenses.

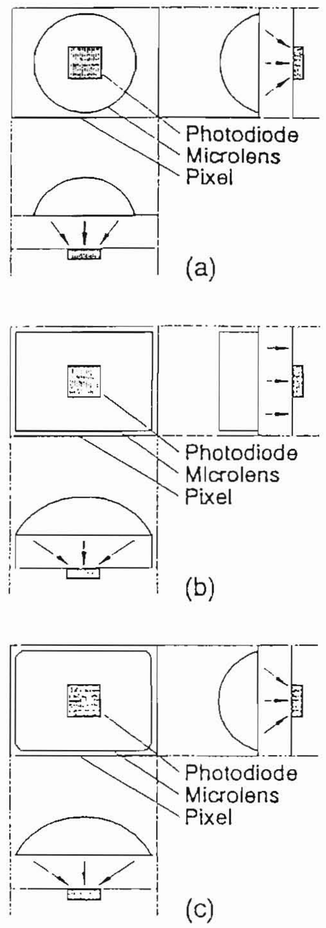

FIGURE 5 Top views and cross sections of the different types of microlenses : hemispherical lens (a), semicylindrical lens (b), and rectangular dome lens (c).

The focal length of microlenses is another important factor for designing the effective aperture ratio. Microlens with short focal length (thick lens) provides higher gain in aperture ratio. This is due to that the lateral magnification of the short focus microlens can be small, especially for rectangular dome microlens, it has two different focal lengths in two orthogonal dimension, only a thick lens is able to keep the two different focal length in an acceptable range. The result of effective aperture verses microlense thickness is shown in Fig. 6, the effective aperture increases with the lens thickness, and thin lenses have very poor aperture ratio. There is another reason to choose thick (short focal length) microlenses, the incident ray angle and the position error of microlens can cause large amount of light shading, this problem is more serious for long focus microlenses.

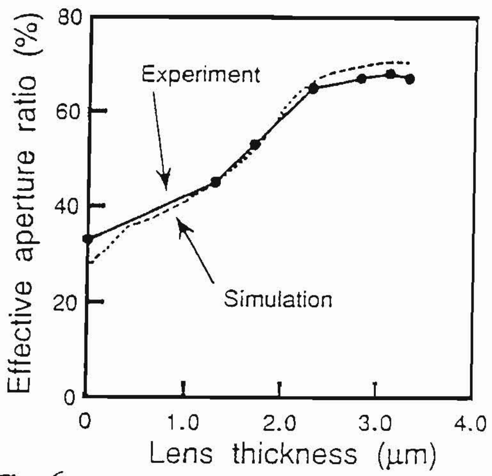

Fig. 6 Relation between the effective aperture ratio and the lens thickness for 0.8μm spaced rectangular dome - lens array.

3). Optical cross talk induced by microlenses

As mentioned above, thick microlenses are relatively easy to fabricate and can reach high effective aperture ratio. But there is a severe drawback for using thick lenses for imager sensor: it will raise optical cross talk and noise level. As shown in Fig. 7, if an off optical axis incident beam is incident on the left microlens with an incident angle ϑ at air/lens interface, the transmitted beam will enter the microlens at an angle ϑ', the reflected beam will be incident on the next microlens at an angle φ and enter the next microlens at an angle of φ'. At areas close to the edge of the microlens, the incident angle ϑ becomes big, and a large percentage of this light beam would be reflected at the lens surface, and enter the neighboring lens to reach other pixels. This stray light may enter the photosensitive area of the next pixel, or of the second next pixel, or of even further away pixels to generate the optical cross talk and raise optic noise level. The percentage of photons spread into the photo-active area of neighboring pixels can be calculated as

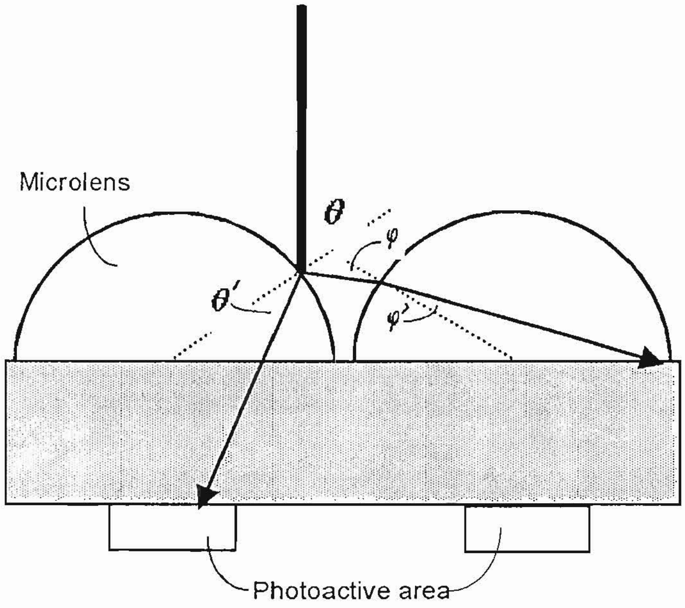

Fig. 7 Light reflected from the surface of microlenses can reach the neighboring pixels to generate cross talk and noise level.

$$\frac{I_{s,p}}{I_{os,p}} = \int\int R_{s,p}(\theta) T_{s,p}(\phi) 2\pi A sin(\theta) \cos(\phi) d\theta d\phi$$

Here the subscript s indicates the s-polarized light, subscript p indicates the p-polarized light. $I_{os,p}$ is the intensity of the total light incident on one microlens, and $I_{s,p}$ is the intensity of the stray light enters the photo-active area of neighboring pixels. $R_{s,p}(\vartheta)$ is the reflection from the microlens and $T_{s,p}(\varphi)$ is the transmission to the neighboring microlens. A is a factor related to the spacing of the microlenses, usually close to 1.

Using a simple model, which assume that the microlenses are hemispherical and the incident light is a plane wave, calculation shows that for s-polarized light, the stray light entering the neighboring photo-active areas is bigger than 3%, while for p-polarized light, the stray light entering the neighboring photo-active areas is less than 1%. This effect will induce optical cross talk and noise to damage the image quality. For example, if a small dark object sits close to a big bright object, this dark object would be smeared out by such optical cross talk. This effect can not be eliminated by an anti-reflection coatings, because the anti-reflection coatings only work with flat surface. This effect has been confirmed by discussing with Olympus America Inc.[22], they find that the cross talk induced by microlens reflection is 1~2% for unpolarized light using their program. For a real image system, the incident light is not a parallel beam but has certain angle, the optical cross talk could be even worse.

3. The micro-wedge optical concentrators (μ-WOC)

Micro-wedges have been used in optoelectronics for many years, for example, submicron metal tips for field emission display[23], wedge interference filter[24,25], holographic wedge detector[26], wedge-shaped nonlinear cladding[27] and wedge shaped traper for optoelectronically integrated circuit[28]. Recently, JPL has invented a technology of using micro-wedge optical concentrators (μ-WOC)on solid state image sensors to increase the aperture ratio to about 100%[29]. This μ-WOC technology also can be used for IR and UV sensing.

1). Basic structure of μ-WOC

Consider a group of long wedge shaped strips are built upon a solid state image sensor chip and the cross section is shown in Fig. 8, these micro-wedges cover all of the readout circuit areas and leave the photo-active area open. The surface of the micro-wedges are coated with reflective metal coatings. When the image light is incident on this device, the photons move toward the photo-active areas will be collected by the photo-active areas, the photons move toward the readout circuit area will fall on the walls of the micro-wedges, be reflected once or several times and finally go into the photo-active areas. Therefore, almost all of the incident photons can be collected by the photo-active areas. Because μ-WOC is working on reflection mode, it is able to function well in both UV and IR range. In addition, μ-WOC structure can also reduce the optical cross talk since the photo-active areas of different pixels are separated by the μ-WOCs.

2) The lateral aspect ratio of μ-WOC

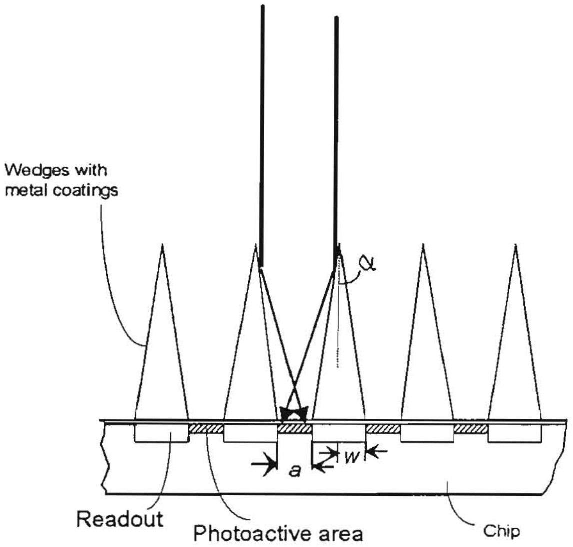

Fig. 8 Cross section of micro-wedge concentrator, photons toward the readout area will be reflected by the wedges and finally reach the photoactive area.

The aperture ratio of μ-WOC depends on several factors, the reflectivity of the metal coating, the smoothness of the metal coating, the dimension and shape of the photo-active area, and the lateral aspect ratio (the ratio of the length of a structure in the plane of the wafer to its width in that plane). The lateral aspect ratio is a very important factor of μ-WOC, if the aspect ratio is too low, many photons, especially those photons with big incident angles will be reflected back and never reach the photo-active area. General speaking, the bigger the aperture ratio, the higher the aspect ratio is needed. But there might be a fabrication problem for making very high and thin μ-WOCs. To decide the aspect ratio, we need to consider the shape of the photo-active area, the smaller the photo-active area, the higher aspect ratio is needed; and the f-number of the image lens, the smaller the f-number, the bigger the aspect ratio is needed. For an ideal triangle shaped wedge, the aspect ratio A=1/(2tanα), where α is the half angle of the tip of the wedge. If the incident light is perfect collimated, then maximum half angle α and the minimum aspect ratio can be estimated by equations:

$$\frac{a}{\tan\frac{4\alpha}{\tan\alpha}-1}=\frac{\frac{w}{\tan\alpha}-\frac{a+w}{\tan 2\alpha}}{\frac{1}{\tan\alpha}+\frac{1}{\tan 2\alpha}}$$

and $A=1/(2\tan\alpha)$.

here a is the linear width of the photo-active area and w is the half width of the readout area. For example if the width of the photo-active area is 30% of the pixel width, then the minimum aspect ratio is 1.6; if the width of the photo-active area is reduced to 25% of the pixel width, the minimum aspect ratio is increased to 2.1. The smaller the photoactive area, the higher aspect ratio is required. For a real image system, the incident light is not parallel but has certain angle, the bigger the incident angle, the higher aspect ratio is required. Further study is needed to determine the aspect ratio for a real image system.

3) 2-D μ-WOC

The 1-D μ-WOC structure as discussed above is able to collect all of the photons in one direction, which is the direction along the wedge groves, while the photons in the other direction can not be all collected; similarly it can eliminate the optical cross talk in the direction perpendicular to the wedge groves, but may increase the optical cross in the direction along the wedge groves. To reach better photon collection efficiency and eliminate all of the optical cross talks, a 2-D μ-WOC structure is introduced as shown in Fig. 9. Two set of wedge groves are built in cross direction to form many small funnels, one on top of each pixel. The walls of the funnels are coated with highly reflective metals. Each funnel functions like a waveguide, the photons fall into the top opening of the funnel will be guided to the photo-active area. This structure can have the aperture close to 100%, and all of the optical cross talks can be eliminated.

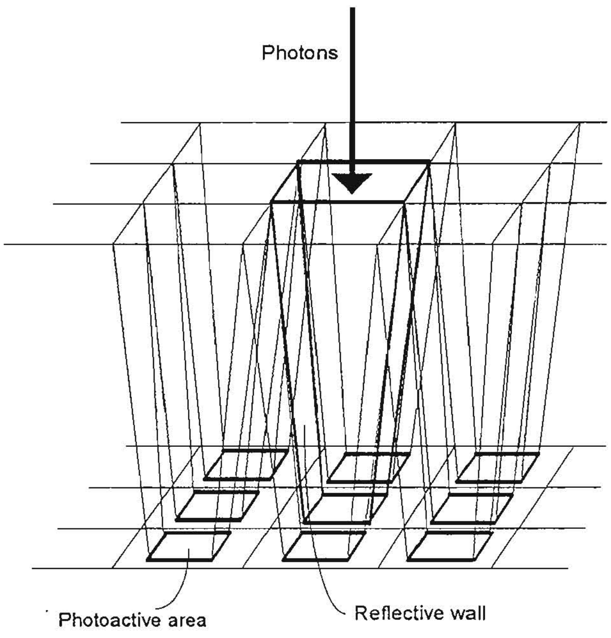

Fig. 9 The 2D structure of micro-WOC, the reflective walls function like wave guides, all the photons fall into the opening of the funnel will reach the photoactive area.

This μ-WOC structure may be also used for display devices, such as active matrix liquid crystal display(ALMCD) device. The ALMCD has similar structure with solid state image sensors, it needs to build transistors and connection lines, which take over 30~50% of the panel area and blocks out the light. If the μ-WOC technology is applied there, the aperture ratio can also increased to close to 100%..

4) Fabrication of μ-WOCs

In last ten years, micromachining especially silicon micromachining has blossomed into a vital industry with numerous practical applications. Surface micromaching, silicon fusion boding, and process called LIGA (a German acronym for Lithographic, Galvanoformung, Abformung -- in English, lithography, electroforming, molding) have evolved into major micromiching technology. Many exotic structures of very high lateral aspect ratio -- lateral dimensions of few micrometers and vertical dimensions up to 1000 μm can be built[30]. Threre are several possible fabrication method to build μ-WOCs, such as grey-tone lithography[31] and the processing sequence employed by betsui to form a self aligned silicon emitter array[32].

Another method, proposed by JPL, is to use non uniform current distribution electroplating process. For electroplating, general speaking, the deposition thickness is proportional to the electrical current density, the higher the current density, the thicker the metal deposition. Consider the electrical current between a line (the anode) and a plate (the cathode) submerged in a solution, as the cross section is shown in Fig. 10. The electrical field is stronger in the middle of the plate,and weaker at the edges of the plate. Since the conductivity of the solution can be considered as a constant, the current distribution should be higher in the middle of the plate and lower at the edge of the plate. Therefore, more metal deposit in the middle than at the edge, and a little hump is formed on the plate as the curve 1. After the deposition like curve 1 is formed, the center of the metal hump is even closer to the anode than the edge of the metal hump, this leads to a stronger electrical field and higher current density, more metal deposition in the middle to form a wedge as shown in curve 2. This process becomes a positive feedback, the thicker the deposition, the higher current in the middel, the steeper the wedge. To optimize this process, the distance between the line and the plate should be small at start, and the line slowly moves back with the wedge growth. For 1-D μ-WOC, the anode should look like a grating instead of a single line, and for 2-D μ-WOC, the anode should look like a grill. These anodes can be made by lithography. Experiment study is needed.

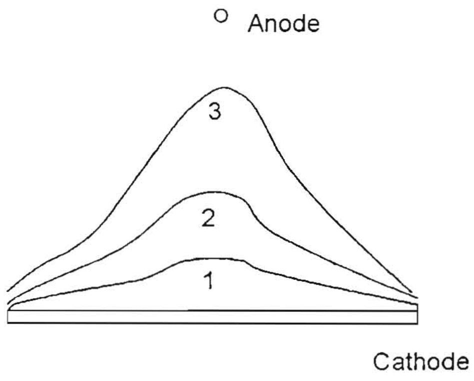

Fig. 10 Fabrication of micro-wedges using no uniform current distribution electroplating.

4. Conclusion

Aperture ratio is an important characteristics of solid state image sensors, especially for the small image sensors. Microlens technology with melting process has been proposed by many people, it can raise the aperture ratio of an image sensor from less than 30% to near 70%. But we find there is a severe draw back due to the optical cross talk induced by microlenses, such optical cross talk is usually more than 1% and it depends on the light polarization. Though the microlens technology has been proposed for low cost consumer electronic cameras, it may not suitable for high quality image sensor, especially not for those sensors used for scientific and military purpose. On the other hand, a new technology of μ-WOC for solid state image sensor has shown strong merits, it can increase the aperture ratio close to 100% without raise optical cross talk. The μ-WOC technology can also be used for UV and IR image sensors since it employs the reflection mode. In addition, the μ-WOC technology may also be used for other electro-optical devices, such as active matrix liquid crystal display, to increase the aperture ratio.

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