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Near-field assisted nanoscale patterning for improved absorption in thin film silicon solar cell

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ABSTRACT

Near field optics concepts have introduced a paradigm shift in a wide variety of engineering fields in the recent past and the most significant applications of this fundamental physics concepts have been in the applied engineering problems such as improved broad band light absorption thereby enhancing the conversion efficiency of thin silicon solar cells. Also, for writing patterned structures or features using non contact optical methodologies have enabled near field optics assisted fabrication and related applications. The technology involving optics concepts and methodologies targeting energy sector have seen the impact of the same with a challenging trend to achieve smaller features or devices with micro- or nano-scale features. This demands automatically the need for achieving much smaller features beyond the forecasted sub- 30nm feature patterning methodologies. To meet such demands, a new branch of near- field optical concepts for improving patterning resolution has started developing which have been receiving considerable attention for its ability to produce high density sub-wavelength features that can find tremendous energy harvesting applications. This paper in this context mainly focuses on the review of different near field optical concepts and approaches developed for patterning by the author's group at NTU. Different concepts were explored incorporating surface Plasmon waves (LSPs, SPPs, LRSPs), gap modes as well as their interference in order to high resolution features and pattern dimensions at nano-scales. The absorbance of near band gap light is small and hence structuring of thin film solar cell is very important for increasing the absorbance by light trapping. The manuscript conclude by correlating the above said aspects and the challenges in achieving improved light conversion in thin film solar cells.

Keywords: near field optics, plasmonics, thin film silicon, solar cell, absorption efficiency

1. INTRODUCTION

Device manufacturing in the semiconductor and energy industries in the recent past has seen the challenging trend to realize devices with micro- or nanoscale features. This requirement has led the need for achieving the forecasted sub-30nm fabrication methodologies. Researchers and lithographers have revisited either conventional techniques or modified the existing configurations, with original contributions[1, 2]. Interference Lithography (IL) is considered as one such efficient yet relatively inexpensive technique for fabricating large-area patterns with micron scale or submicron scale periodicities. In a conventional laser interference lithography the feature size achievable is limited by the diffraction limit. A method to go beyond diffraction limit is to use the near filed interference based on Surface Plasmon Resonance in metal[3-7].This branch of near- field optical concepts for improving patterning resolution has started developing which have been receiving considerable attention for its ability to produce high density sub-wavelength features[8, 9]. In this regard, these near filed techniques have been further explored to obtain smaller feature size, higher resolution and higher exposure depths in various configurations [10-13]. These methods are based on exploiting the coupled interaction between Surface Plasmon Polariton (SPP) modes at various layers in metal-dielectric multilayer geometries to tailor their mode characteristics. To achieve a better performance, these methods should be improved so that they can be employed in practical relevant applications in industries such as those for the semiconductor and energy sector.

In the case of energy sector, harvesting and storage of energy based on photovoltaics have invoked tremendous interest as a possible solution for anticipated future energy problems. Various materials such as quantum dots, semiconducting nanostructures and conjugated polymers have been extensively researched in recent times for next generation photovoltaics[14-16]. However, crystalline silicon became the basic proven material for high-efficiency stable.

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photovoltaics [17, 18]. However, the price of solar cell found to be a factor due to the higher costs of silicon material processing techniques. In this context, thin film solar cells found great interest because of its smaller film thickness and cost effectiveness. Usually polycrystalline or amorphous silicon are used as active materials in thin film solar cells because of their lower cost, nontoxicity, abundance and advanced processing technologies. But, carrier diffusion length is very short and the absorbance of near bandgap light is small in these thin film solar cells, resulting in lower absorption and conversion efficiency. Increasing the film thickness by few micrometers is not feasible as recombination rate would be high. Hence, thin film solar cells need to be structured properly to trap more light in order to increase the absorption. Various configurations to increase the optical path length inside the active silicon layer by texturing front or back surface has been investigated in recent times [19-25]. In configurations which rely on front surface texturing, absorption is enhanced by scattering from patterned metal or dielectric structures at the front surface [21, 23, 24, 26]. Enhancing the percentage reflection by back surface texturing has also been widely reported in literature [23, 27]. Various plasmonic concepts are also been widely used in thin film solar cells to achieve enhanced light localization and hence improved absorption [28, 29]. These include scattering by employing nanoparticles inside active layer, localized surface plasmon (LSP) excitation using nanoparticles and surface plasmon Polariton (SPP) excitation at metal semiconductor interface. Recently, enhanced light confinement is reported to be possible by the excitation of gap modes in metal particle-surface system [30].

This paper in this context gives an overview of the different conventional and near field optical concepts and approaches and their interference to pattern high resolution features with dimensions at the micro- and nano-scales [1, 5, 31-33]. Finally such periodic structures' applications combining with plasmonic concept will be discussed which is expected to contribute towards the energy harvesting sector.

2. LASER INTERFEROMETRIC PATTERNING – AN ANALYSIS

Investigations were initially carried out using UV and DUV laser assisted interferometric configurations to fabricate grating (Fig 1). A multiple beam interference lithography (MBIL) equipment (See Fig. 1.) has been configured and developed recently with which two-beam and multiple beams up to five beams can be used for interference with which features at the micro and nanoscale can be written by properly incorporating appropriate methodology. It is to be mentioned that near field optics concepts can be integrated into the MBIL using the modified methodology as shown in Fig 1b. Figure 2b shows the patterned grating structure obtained using the MBIL in a two-beam LIL configuration. Periodic features with approximate half-pitch resolution of 136 nm were experimentally obtained using 364 nm illumination wavelengths. However, LIL was unable to pattern high resolution (sub-100 nm) periodic features using near UV illumination wavelength sources.

Figure 1. (a) Multiple Beam Interference Lithography Configuration (b) Adopted configuration for near field optics

Figure 2. Two-Beam Laser Interference Lithography – (a) Schematic representation and (b) AFM representing the patterned grating feature

3. NEAR FIELD OPTICS ASSISTED PATTERNING

The evanescent wave (EW) and plasmonic interference is investigated here as one of the near field optics techniques. Using exposure of two beams evanescent waves interference, fabrication of periodic line features, with average line width (measured as FWHM) as small as 55.6 nm and average pitch size of 107.15nm, is demonstrated using the MBIL. Employing the two p-polarized incident beams configuration, the line features obtained showed larger average depth and higher aspect ratio than that obtained using two s-polarized incident beams configuration. Close agreement between the simulation and experimental results in terms of the features pitch size and distribution is observed. However, the obtained exposure depth (height) and contrast of the patterned features is found to be poor compared to LIL[32, 33]. In order to enhancing the decaying evanescent field at the prism/photoresist interface, a multiple beam (two and four) surface plasmon (SP) interference generation configuration introduced using the Fig 1b. Figure 3 illustrates that SPIL provide long exposure depth and good intensity contrast as compared to evanescent wave interference lithography [33].

Figure 3. Surface Plasmon Interference patterning. (a) 4-beam SPP interference in Al, (b) 2-beam SPP interference in Al [4]

A minimum feature size of 82nm with a maximum exposure depth of 200nm was able to achieve with this proposed approach. However, there need to be an improved penetration along the Z-axis so as to obtain high aspect ratio features. The next section briefly describes some of these aspects from an FDTD simulation perspective.

4. RESOLUTION AND EXPOSURE DEPTH ENHANCEMENT USING LRSP

A Surface Plasmon Polariton (SPP) is a bound electromagnetic mode that may exist at metal-dielectric interface when excited with required momentum matching condition at the interface. In the case of a thin metallic film confined by two identical dielectric claddings, SPPs are generated at each metal-dielectric interface. For a sufficiently thin metallic layer which is confined between two similar dielectric layers, the SPPs at each metal-dielectric interface couple each other to produce symmetric and anti-symmetric modes inside the metal known as Long Range Surface Plasmon (LRSP) and Short Range Surface Plasmon (SRSP), respectively. The coupling between these SPP modes inevitably leads to the modification in dispersion characteristics of these modes. The modal index (The ratio of light velocity in vacuum to the phase velocity of the guided mode) of LRSP is lower than SPP mode and that of SRSP is higher than SPP mode. This results into a weak mode confinement for LRSP and strong mode confinement for SRSP inside the metal. The weakly confined LRSP has only a small fraction of electric field inside the metal and hence a higher propagation depth into the dielectric. Higher field penetration into the dielectric layer is beneficial for a near field interference lithography[12]. Similar to a single metal layer configuration, a metal-dielectric multilayer configuration also has large number of coupled modes present at the interfaces[34]. The field distribution in such geometries can be effectively excited to generate sub-wavelength field patterns in interference near field lithography application. In this regard, here a metal-dielectric layer configuration is employed as a mode field engineered geometries to excite the LRSP modes in them and hence to obtain improved performance in a two beam and four beams SPP near field interference patterning.

4.1 System configuration and Analysis

The configuration for the LRSP excited metal-dielectric configurations is shown in Fig.4. The configuration consists of two metal layers and three dielectrics. The lowest dielectric is taken as the photoresist (PR) layer, where the pattern is to be recorded.

Figure 4. Schematic of metal-dielectric multilayer SPP interference lithography configuration

The near field interference patterns are simulated using Finite Difference Time Domain (FDTD) method. The frequency dependent material parameters are chosen for metal, dielectric and photoresist layers[35]. A high index prism of refractive index 1.934 is used in the simulation. The PR thickness is taken as $1\mu\text{m}$ with refractive index set to 1.7. For a silver metal film of thickness 50 nm, the surface plasmon resonance angle is observed to be 62° and 69° at incident wavelengths 446 nm and 364 nm, respectively. The electric field intensity distribution in a two beam interference at 364nm and 446nm wavelength are shown in Fig.5. The periodic grating patterns obtained has a half pitch of 55 nm and 65 nm at 364 nm and 446 nm wavelengths, respectively. The electric field enhancement factor is observed to be higher at 446 nm when compared to 364nm.

Figure 5. Electric field intensity distribution of two beam LRSP interference in metal-dielectric configuration at (a)446nm and(b)364 nm wavelength.

It is observed that the electric field is highly enhanced at the PR layer for LRSP interferences. The coupling between modes is maximum when the upper dielectric layer refractive index is similar to the photoresist refractive index. The electric field decay in LRSP interference has a higher penetration depth into the PR layer while keeping a high fringe contrast (>0.8) up to 700 nm. Figures 6(a) show the electric field decay depth in SPP interference and LRSP interferences. Four beam interference patterns are generated in this metal-dielectric multilayer configuration. Figure.6 (b) shows the obtained four beam interference pattern in PR layer at 5nm below the surface. The experimental part of this work is in progress.

Figure 6. Electric field decay in LRSP and SPP interference.

5. IMPROVED LIGHT ABSORPTION IN THIN FILM SOLAR CELL

The main objective here aims at enhancing the absorption and conversion efficiency of thin film silicon solar cells. Thin film solar cell employing different configurations can be realized with such periodic grating structures. An FDTD analysis was carried out on such configurations with and without back grating, having metal nanoparticle above the back reflector and above the metal grating back reflector. An increment of 10.53% compared to planar Al-Ag system and 14.4% compared to conventional solar cell with planar back layer was observed recently[36].

A thin film plasmonic layered structure configuration employing plasmonic normal modes can be integrated with such configurations for seeking enhanced light absorption. A detailed analysis is being carried out using good aspect ratio structures as periodic and random layers in thin film silicon solar cells that can further improve the absorption efficiency.

6. CONCLUSION

Several conventional and near-field optical lithographic techniques have been developed for achieving patterning resolution to meet the forecasted technological nodes. This paper in this context gave a brief overview of the different conventional and near field optical concepts and approaches developed by the authors group at NTU. One of the current foci of the world is to tap natural resources for energy. Improved absorption and conversion of solar energy in different configurations are of prime importance. In this context, comes photovoltaics which is a promising technology that may make a considerable contribution to solve the next generation energy problem. However, the price of the solar

cell is not cost effective due to the costs of silicon materials and processing. Thin film solar cells have taken importance and great interest in solar cell market because of the small film thickness. The limitation however lies in the fact that the absorbance of near bandgap light is small. Structuring of thin film solar cell is very efficient for increasing the absorbance by light trapping. Different types of patterning (structuring) using near field optics are analysed here for their potential applications in thin film silicon solar cells. This paper briefly reviewed the above detailed aspects and the work done in this direction by the author's group in achieving improved light conversion in thin film solar cells.

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