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Design principle of super resolution near-field structure using thermally responsive optical phase change materials for nanolithography applications

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ABSTRACT

The super resolution near-field structure (Super-RENS) which is composed of a thin layer of a thermally responsive optical phase change material (PCM) between two dielectric layers, can be a means of resolving the limited resolution of the laser beam for direct laser lithography. In Super-RENS, incident laser irradiation induces the direct, reversible opening and closing of a nanoaperture in the PCM layer, and a nanoscale pattern is realized in the lithography system. Here, we first introduce the complete modeling procedures and optimization methodology for Super-RENS in nanolithography based on a rigorous analysis of near-field structure, thermal analysis in the finite-element method, and analysis of the corresponding feature size on the photoresist (PR) layer. Multiple combinations of the PCM layer and the two dielectric layers with varying dimensions are considered as design parameters to achieve the required resolution in the nanolithography system. The feasible line profiles are investigated at the general operating conditions of the pulsed laser beam, based on varying dimensions of the PCM layer (5–30 nm) and the two dielectric layers (10–200 nm). This work will provide a detailed methodology for the design and optimization of the Super-RENS for applications in the nanolithography system.

1. Introduction

Direct laser lithography is widely used as an essential technique in high-speed fabrication procedures in the various industrial fields, as well as in diverse research areas. More recently, following technological advances in recent decades such as the development of terahertz (THz) materials [1], the requirement for pattern size reduction to the nanoscale has increased. However, pattern size resolution is intrinsically limited by the diffraction limit of the incident laser light, because the resolution of a laser with a Gaussian profile is determined by both wavelength and numerical aperture (NA), which yields the spot size of the focused laser beam. From a different perspective, in terms of lithography effectiveness, the conventional fabrication methods for micro/nanopatterns generally depend on mask arrays as pre-designed patterns, which has resulted in high-cost and delayed processes in various applications. To overcome the fundamental limitations of conventional lithography techniques, various approaches to engraving nano-size patterns using maskless lithography have been developed, such as scanning electron beam lithography, focused ion beam lithography, multiaxis electron-beam lithography, interference lithography, dip-pen lithography, scanning-probe lithography, zone-plate-array lithography, and maskless optical-projection lithography [2]. Specifically, scattering-type super-RENS uses metal particles in gas bubble-pit formed in the process to enhance the near field [3]. Thermally-induced optical nonlinear effect-induced super-resolution through Te-based or Sb-based PCM materials utilizes crystal-to-amorphous transition which is caused by thermal energy due to the optical nonlinear effect for further enhancement of resolution [4,5].

However, the super-resolution near-field structure (Super-RENS) approach [6–9], which was developed for use in optical data storage systems by Tominaga et al. [10], can be applied to laser-nanolithography systems as a new method of overcoming intrinsic limitations through the formation of dynamic nanoapertures. Specifically, Super-RENS is composed of a thin layer of a thermally responsive optical phase change material (PCM) sandwiched between two dielectric layers (Fig. 1a). The *z*-axis represents the laser irradiation direction, whereas, the x and y axes indicate the orthogonal direction [11]. Kuwahara et al. reported that the nanoaperture on super-resolution could be formed by melting phenomenon, based on the measured complex refractive indices of Sb_2Te_3 in liquid state [12,13]. The PCM is thermally activated and deactivated by a reversible transition from the crystal to the amorphous phase, which generate thermally-induced optical nonlinear effects at a specific temperature [14–18] and vice versa, when the thermal energy from the laser irradiation is absorbed into this layer (Fig. 1b). In Super-RENS, the meaning of the amorphous phase is distinguished from the conventional definition.

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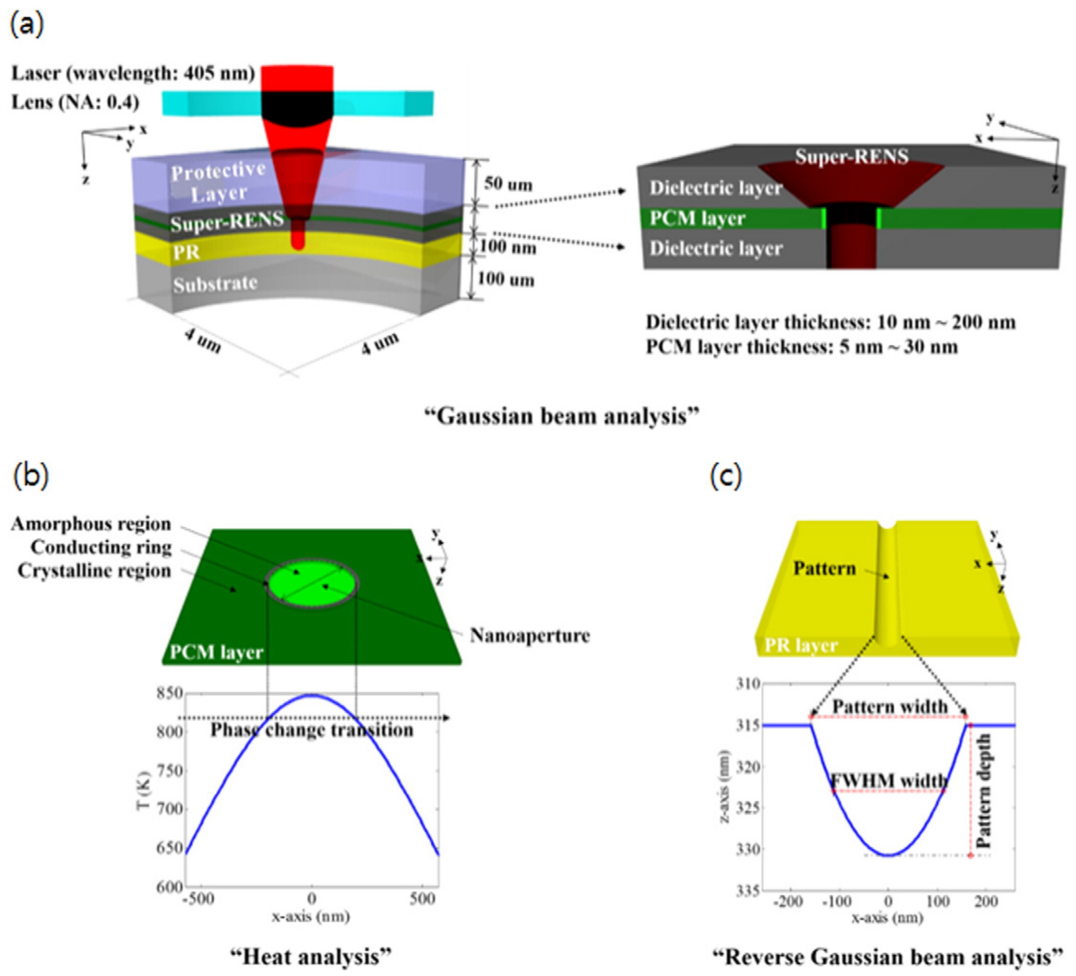

Fig. 1. Description of photo-thermal simulation procedures. (a) Scheme of nanolithography systems and the extended inner layers of Super-RENS. (b) Phase change transition between crystalline and amorphous phase in PCM, depending on the temperature distribution. (c) Analysis of pattern profiles on photoresist in nanolithography using Super-RENS.

The amorphous phase or state in Super-RENS indicates that the refractive index is significantly change due to the transition of bandgap and interspacing in the PCM layer, while the crystalline phase maintains its resonant bonding [14]. Many theoretical and experimental investigations has been conducted to explain the thermally-induced optical nonlinear effects [19–22]. The laser beam can pass through the amorphous region over a threshold temperature without a major loss of intensity, because the imaginary component of the refractive index, which determines the laser power absorbance, decreases significantly. Inversely, the crystal region of the PCM layer in Super-RENS significantly blocks the penetration of the laser beam under a threshold temperature. In Super-RENS, the two dielectric layers play the role of thermal insulators and control the laser focusing on the photoresist (PR) layer, which is placed under the Super-RENS in nanolithography systems [14]. The incident laser beam (with a Gaussian profile) can manage the temperature distribution of the thermally responsive optical PCM. Then, the corresponding amorphous region, which functions as the nano-size aperture, is gradually opened at the center position of the incident laser beam over the threshold temperature, because the maximum intensity is located at the center position in a Gaussian laser beam profile [23–26]. The transition between the amorphous and crystal phases is reversible at the critical temperature in a thermally responsive optical PCM. Furthermore, the boundary between the crystal and the amorphous phases shows the metal-like behaviors which induce the surface plasmon effect, because the phase mismatch and the thermal energy at the interface [14]. Thus, the dimensions of the amorphous region, which determines the minimum resolution of the pattern size on the PR layer, is dominated by the temperature distribution in the PCM layer (Fig. 1c). This enables the high resolution nanolithography to overcome the diffraction limit [27]. The experimental works from other literatures have provided the feasibility of nanolithography system using Super-RENS. Super-RENS was initially developed as a platform for the enhancement of the near-field intensity and the reduction of the focused spot size, experimentally [28,29]. The effectiveness of Super-RENS was continuously confirmed that the increase of laser power in the scanning near-field optical fiber probe method reduced the squeezed spot size upto 68%, in comparison with the diffraction-limited focusing spot size [30]. Furthermore, the combination of near field microscopy, confocal microscopy, and time resolved pump-prove technique enabled the direct measurement of 100 nm spot size with a 25% decrease of laser power, in Super-RENS [31]. However, despite the potential of this application of Super-RENS to lithography systems, the majority of studies have been limited to analysis of optical data storage applications only.

Herein, we first give a full analysis of nanolithography using Super-RENS based on a thermally responsive optical PCM. For further implementation of Super-RENS to lithography, detailed modeling and optimal design at certain PCM and dielectric layer conditions are essential, in order to enhance the resolution and feasibility of this technique. Thus, we develop a theoretical modeling approach and an optimization methodology for Super-RENS in nanolithography applications, from the laser irradiation to the PR patterning stage. Multiple combinations of the PCM layer and the two dielectric layers with varying dimensions are considered as design parameters in order to understand and optimize the Super-RENS lithography system. Rigorous analysis of near-field structure, thermal analysis in the finite element method (FEM), and analysis