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Super-resolution GaAs nano-structures fabricated by laser direct writing

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ABSTRACT

Nanostructures have been applied in various semiconductor devices. However, current nanostructure fabrication technologies always have such or that shortages, stimulating a need for new technology with simple fabrication, high efficiency and low cost. In this paper, we present super-resolution nanostructure fabrication based on laser ablation effects by using laser direct writing technique. GaAs nanostructures including nano-holes, nano-grooves and gratings have been fabricated. The depths and full widths at half maximum of nano-grooves show linear dependence on laser power and pulse duration. The minimum full width at half maximum of grating groove reaches to 32 nm, which is nearly 1/10 to diameter of focused laser spot. The results demonstrate the capacity of laser direct writing technique and provide a simple means for super-resolution nanofabrication.

1. Introduction

Nanostructures have attracted great interests for their wide applications in many fields such as antireflection, photonic crystal and bioengineering [1–3]. A number of techniques including electron beam lithography (EBL) [4], focused ion beam lithography (FIB) [5], nanoimprint lithography (NIL) [6] have been used for nanofabrication. As discussed in previous studies [7,8], all these techniques have advantages and disadvantages. Though EBL and FIB are capable of fabricated nanostructures in high resolution, the fabrication processes are time-consuming and expensive equipments are demanded. NIL is an increasingly mature nano-fabrication technique, but the master molds for NIL are still usually fabricated by EBL or FIB. Laser based lithography techniques are powerful in micro/nanostructures building [9–11]. Patterns are usually fabricated on photoresist and then transferred onto substrates by reactive ion etching. However, due to the diffraction limit of light, the feature sizes of structures fabricated by the technique are generally in sub-micrometer scale. To realize low-cost and high-efficiency nano-fabrication, there is an increasing interest to develop high-precision laser fabrication techniques [12–14]. Laser direct writing (LDW), referring as a mask-less method to create nanostructures on the sample surface, is possible to achieve super-resolution fabrication by taking advantages of nonlinear laser-matter interactions such as two-photon polymerization [12], surface plasmon polaritons [13] and laser ablation [14]. Though resolutions beyond 100 nm have been reported, LDW by two-photon polymerization and scanning near field photolithography are commonly used for nano-patterning on photo-resists. By contrast, LDW based on laser ablation is available for a variety of materials processing including semiconductors, metal films as well as polymers.

GaAs (Gallium arsenide), a III–V direct bandgap semiconductor with a zinc blende crystal structure, has been used in the manufacture of various devices such as microwave frequency integrated circuits, infrared light-emitting diodes, laser diodes, and solar cells [15–17]. With the trend toward miniaturization and performance enhancement of the devices, smaller GaAs nanostructures are desired. For example, to realize antireflection in broad spectrum and wide angle range, nanostructures with sub-wavelength (less than 400 nm) period are demanded [1]. Patterned GaAs substrate for site-controlled quantum dot growth provides another example. Quantum dots nucleate according to nano-pits fabricated on the substrate [6]. Nano-structures with small feature size are capable of defining a high density quantum dot array. The LDW on GaAs are generally making use of multi-beam pulsed laser interference irradiation [8] or focused laser beam scanning [14]. Coherent laser beam interference creates periodic patterns on sample surface. The minimum period in the air is half of the laser wavelength. LDW by focused laser beam scanning are capable of creating arbitrary patterns. The separation for neighboring nano-pits or nano-grooves is dependent on the precise movement of the laser spot on sample surface. Recently, as reported by Huang [14] and Zhang [10], respectively,

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nano-structures with line width of 150 nm and period of 355 nm were acquired on GaAs by LDW.

In this work, super-resolution periodic nano-holes, nano-grooves and gratings are fabricated on GaAs(001) surface using LDW technique based on laser ablation effects. Furthermore, we studied the relationship between groove sizes and laser parameters. The minimum full width at half maximum (FWHM) and period of grating grooves reach to 32 nm and 185 nm, which are smaller than 1/12 and 1/2 to the laser wavelength, respectively. The results demonstrate the capacity of LDW and provide a simple means for super-resolution nanofabrication.

2. Experimental

In experiments, epi-ready undoped GaAs(001) on-axis wafers were used. In order to obtain a high quality surface, native oxide layer was thermal removed and a 300 nm-thick GaAs layer was subsequently grown by using a molecular beam epitaxy (MBE, DCA instruments) system. The growth parameters of substrate temperature, growth rate and As_2 flux were 580 °C, 600 nm/h and 1.5×10^{-6} Torr, respectively. In-situ reflection high energy electron diffraction was used to monitor the sample growth. When the buffer layer growth completed, wafers were taken out of the MBE system and nano-patterned by a LDW system (HWN LDW-P1500). The system was equipped with a 405 nm laser and objective lens. Laser beam was focused by the lens and created nano-holes on sample surface by a single laser pulse when peak intensity exceeding the GaAs ablation threshold. The LDW process was performed using a pixel-by-pixel movement. As sketched in Fig. 1, beam spot overlapping, i.e., when "Pixel space" is smaller than "Beam diameter", makes nano-holes coalesce to nano-groove. Three group samples were prepared. Firstly, to study the laser-material interaction, nano-hole arrays were obtained. Secondly, nano-groove arrays were prepared to study the line-width and depth dependence on laser power and pulse duration. The pixel density of laser scan line was set to 12,000 mm^{-1}. Finally, different duty cycle and profile gratings with period of 185 nm were obtained with pixel density of 25,000 mm^{-1}. Objective lens with 0.8NA (NA, numeral aperture) was used for first and second group sample fabrication and 0.9NA for the third group. The sample surface morphology was characterized by atomic force microscope (AFM, Bruker instruments) with tapping mode.

3. Results and discussion

Two nano-hole arrays were fabricated with the same laser output power and different pulse durations of 145 mW, 2000 ns and 145 mW, 100 ns, respectively. The AFM images and cross section analyses of nano-holes marked in dash lines are shown in Fig. 2(a) and (b), respectively. The elliptical nano-hole in Fig. 2(a) is with depth of 28 nm, FWHM of 161 nm along long axis and FWHM of 106 nm along short axis. When the laser pulse duration decreased to 100 ns, smaller nano-holes are obtained. As shown in Fig. 2(b), the depth and FWHMs along long axis and short axis are 5 nm, 80 nm and 59 nm, respectively. The AFM system also provided the amplitude error images for measurements. The amplitude errors of nano-holes in Fig. 2(a) and (b) are less than 2.0 nm and 0.4 nm, respectively, which means the range of measurement errors is better than 10%.

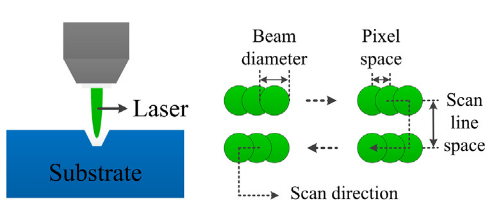

Fig. 1. Schematic diagram of LDW scan process using a pixel-by-pixel movement.

The shape of nano-holes indicates the intensity of laser spot is focused in an elliptical region. This may relate to the inhomogeneous of laser beam and aberration introduced from objective lens [18]. To minimize potential negative effects of anisotropic laser spot, all nano-grooves were fabricated by scanning along the elliptical long axis. Studies [19,20] have suggested that photo-thermal effects dominate the laser-material interaction if the photon energy is above the semiconductor bandgap energy. In our experiments, laser with wavelength of 405 nm generates photons with energy of 3.06 eV, which is above the GaAs bandgap energy of 1.42 eV. Therefore, the laser energy absorbed by GaAs will mainly translate to heat. The photon energy absorption efficiency is dependent on the surface reflectivity (R) and absorption coefficient (α). Here, for wavelength of 405 nm and perpendicular irradiation, R is 0.47 and α is 6.1×10^5 cm^{-1} [21]. As increasing of substrate temperature, GaAs is melted. When more energy is accumulated, the melted material will be removed or evaporated from surface. Therefore, laser ablation threshold should be close to but higher than that of melting. In our experiments, because the focused laser spot has an approximate Gaussian distribution in energy, the energy intensity only at center region of laser spot exceeds laser ablation threshold when appropriate laser parameters are selected as shown in Fig. 2(b). Correspondingly, melting and ablation regions are also clearly observed in the image as marked by dash ellipse. Additionally, due to higher evaporation rate of Arsenic than that of Gallium, Gallium-rich phase at laser ablation regions have been reported [8]. MBE is a frequently-used crystal growth technique, high-quality GaAs buffer layer can be achieved by the technique. Therefore, in the process of LDW nanofabrication, crystal GaAs was kept well at un-patterned regions while Gallium-rich material was formed on the surfaces of laser ablation induced nano-holes.

The LDW based on laser ablation effects creates nano-holes smaller than the focused laser spot. The focused spot size can be estimated by Airy disk, whose diameter is calculated by formula $D = 0.61\lambda/NA$. For our LDW system with a 405 nm laser, the diameters are 304 nm and 270 nm for lens of 0.8NA and 0.9NA, respectively. Airy disk presents ideal status considering diffraction effect, while actual focused laser spot may be elliptical shape. In our case, long axis and short axis of the elliptical nano-hole shown in Fig. 2(b) are 170 nm and 127 nm, obviously much smaller than Airy disk diameter of 304 nm, demonstrating the ability of LDW to achieve nano-fabrication with a high resolution beyond optical diffraction limit. The Airy disk also provides an opportunity to estimate the average power density of focused laser spots. Because of the energy loss mainly resulted from spatial filtering in the optical system, 1/12 of the laser output power was transmitted to sample surface. Take the laser parameters (output power of 145 mW and objective lens with 0.8NA) used in Fig. 2 for example, the average power density was 1.67×10^{11} W/m^2. The result is in the same order of magnitude compared with the previous study [10].

The nano-grooves can be formed by coalescing of nano-holes. Fig. 3 shows two AFM images and average cross sectional profiles of the second group samples. In Fig. 3(a), when laser pulse with parameters of 125 mW and 1000 ns was applied, nano-grooves with average depth of 17 nm and FWHM of 105 nm are clearly observed. Increasing laser power and pulse duration to 130 mW and 10,000 ns creates deeper and wider grooves as shown in Fig. 3(b). In order to study groove size dependence on laser power, the pulse duration is fixed at 10,000 ns. For power increasing from 112 mW to 130 mW, as shown in Fig. 4(a), both the average depth and FWHM increase linearly from 16 nm and 90 nm to 121 nm and 129 nm. For investigating duration dependence, the power is fixed at 130 mW. Linear dependence is also observed as shown in Fig. 4(b). In the range of 100–900 ns, the average depth and FWHM increase from 8 nm and 84 nm to 47.6 nm and 112 nm.

The relationship between nano-groove size and laser parameters is discussed by photo-thermal model in this paragraph. The isotherm of ablation depends on the energy balance of laser absorption and heat diffusion. When increasing pulse duration, more photo energy