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Fabrication of GaSb Microlenses by Photo and E-beam Lithography and Dry Etching

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Abstract. Fabrication of surface-relief microstructures in GaSb for application in mid-infrared optoelectronic devices is described. Photo- and e-beam lithography was used to define patterns on GaSb surfaces. Ar/O_2 sputter etching and RIE in BCl_3-based plasma were applied to transfer preshaped master into the GaSb substrate. Circular microlenses with an aspect ratio (height to diameter) 0.4/10 μm and circular gratings with 0.4 μm linewidth / 1 μm period and 1.7 μm depth have been demonstrated.

Introduction

GaSb and related semiconductors are well recognised for their potential application in mid-infrared optoelectronics and thermophotovoltaics. Efficient GaSb-based LEDs, laser diodes, and photodetectors have been recently demonstrated [1, 2, 3, 4] as well as TPV cells [5, 6]. With the advent of sub-micron technology, fabrication of surface-relief micro-optical elements monolithically integrated with active semiconductor structures becomes feasible which promises improved characteristics of the optoelectronics devices [7, 8]. In particular, semiconductor microlenses (refractive and diffractive) have the potential to improve the performance of infrared photonic devices. The paper describes the fabrication of etched surface-relief microstructures in GaSb for application at mid-infrared wavelengths. Of particular interest were refractive GaSb microlenses for GaSb-based photodetectors and circular gratings for surface emitting MIR lasers.
To form refractive microlenses in GaSb resist-reflow with subsequent sputter etching in Ar/O_2 plasma has been applied. Diffractive circular gratings in GaSb were patterned by e-beam lithography with RIE in BCl_3-based plasma.

The reflow technique for fabricating refractive microlenses consists of forming appropriate photoresist pattern and transferring them onto GaSb substrates. The pattern transfer process requires precise control of the relative etch rate of photoresist and substrate material to achieve the desired microlenses properties and shape. The second technique, electron-beam lithography, is used to define the pattern mask and RIE transfers the pattern into the substrate. This method requires highly anisotropic etching with high selectivity between material mask and semiconductor substrate.

Experimental

The samples used were (100) oriented GaSb monocrystalline wafers, Te doped to a concentration of $(1\text{-}5)\times10^{17}cm^{-3}$. They were cleaned in hot organic solvents followed by surface pre-treatment consisting of anodic oxidation in $C_4H_6O_6$ - $C_2H_4(OH)_2$ and oxide removal in 5%HCl. Two types of photoresist, namely, ma-P 100 and ma-P 205 and one electronosensitive resist PMMA 940k were used. Spin-coating and hotplate-baking of resists were performed using a 100CB Brewer spinner. Photo- and electron-beam-lithography techniques were used to define lenses pattern.

The circular and square microlenses were exposed using 300 nm UV MJB 3 SUSS align-exposure system. The circular gratings were patterned by e-beam lithography in a JEOL 6400 SEM equipped with Raith pattern generator. Dry etching was performed by sputter etching in Z400 Leybold system or reactive ion etching in XPL 01 Secon Mark 4 equipment. Surface morphology, lens diameter and shape were determined by optical microscopy with Nomarski contrast (Olympus DP12), SEM (Philips XL 30), AFM (Digital Instruments Nanoscope IIIa) and Tencor α-step 200 profiler.

Resist reflow technique

After spin-coating, hotplate baking photoresist layers were exposed and then developed to produce circular (ϕ = 10-14 μm) and square (300×300 μm) microlenses. Fig. 1 shows the fabrication sequence of refractive microlenses by resist reflow technique. Samples were baked in a convection oven at a temperature T = 200°C that exceeds to photoresist glass transition temperature T_G = 120-160°C to reflow the smooth microlens profile. In the case of sputter-etching, using Ar as the sputtering species photoresist tend to have lower erosion rates than GaSb. This is due to low efficiency energy transfer between relatively heavy Ar with atomic mass of 40 and low photoresist atomic mass. We used oxygen background pressure to increase the etching rate of the photoresist.

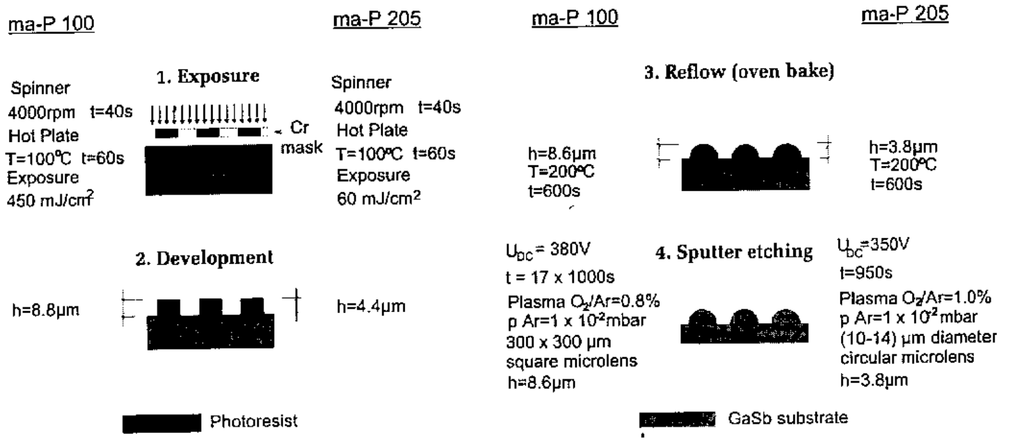

Fig. 1. Fabrication sequence of microlenses by resist reflow technique.

The optimised conditions of the relative etch rates to vary the deep of the photoresist and GaSb, were achieved by controlling the oxygen background pressure and the Ar ion energy. Typical chamber pressure was $p = 1\times10^{-2}$ Torr, DC voltage U_{DC} = w250-380 V, and gas flow ratio f_{O2}/f_{Ar} = 0-0.1 were used to obtain of refractive microlenses.

E-beam lithography / RIE technique

The technique was used to generate micrometer-size diffractive optical elements in GaSb substrate consisting of a 100 μm diameter circular grating of 100 rings of 0.4 μm line width and 1 μm period. A trilayer SiO_2/Cr/PMMA structure was used as the masking material and was etched by a two-step RIE method: Cr/PMMA in CCl_4/O_2 and SiO_2 in CF_4/O_2 plasmas. Each electron-beam defined ring was written by 0.1 μm spaced single-pass lines with dose 200 μC/cm², with the electron beam accelerated by a 30 kV voltage. BCl_3 plasma was used to pattern GaSb substrate.

Results

Plots of the etch depth of GaSb, ma-P 100 and ma-P 205 photoresists as a function of DC voltage (Fig. 2a) and gas flow ratio O_2/Ar (Fig. 2b,c) show that with the increasing value of these parameters the etch depth monotonically increases, except of GaSb on flow ratio dependence (increasing of flow ratio O_2/Ar decreases of etch depth). Analysis of the results indicate that optimised sputter etching conditions for GaSb lenses are: $U_{DC} = 350$ V, $f_{O2}/f_{Ar} = 0.01$ for circular lenses and $U_{DC} = 380$ V, $f_{O2}/f_{Ar} = 0.008$ for square lenses.

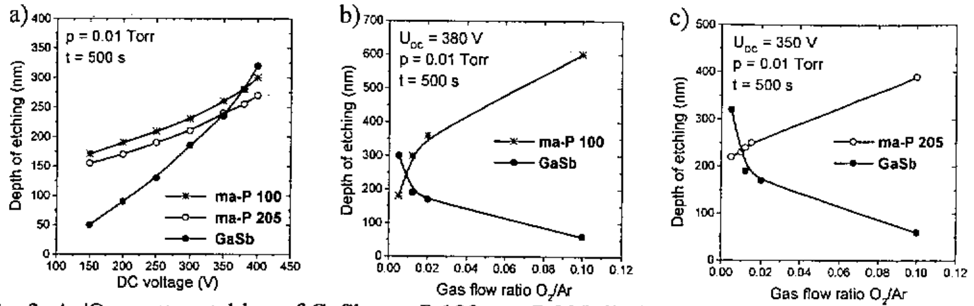

Fig. 2. Ar/O_2 sputter etching of GaSb, ma-P 100, ma-P 205 discharges. Influence of: a) DC voltage, b, c) gas flow ratio O_2/Ar.

Fig. 3a and Fig. 3b compares the surface profiles of the master and replicated 10 μm circular microlenses and show that the initial photoresist thickness decreased during the thermal cycle about 14% (T = 200°C, t = 10 min). Fig. 4a shows SEM image of 10 μm circular microlenses GaSb substrate. The high quality surfaces of GaSb circular microlens is shown in Fig 4b. The surface roughness of GaSb substrate and circular microlens was about 3 nm. Optical photograph of 300×300 μm square microlenses in GaSb is shown in Fig. 4c.

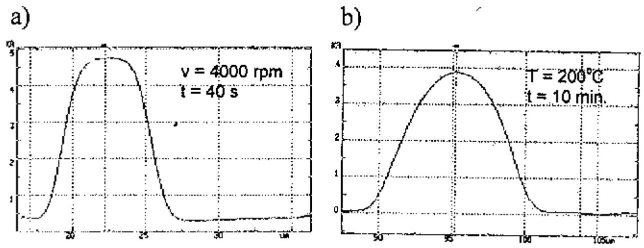

Fig. 3. Profiles of a preshaped lens before (a) and after reflow (b) for 10 μm circular microlenses in ma-P 205 resist.

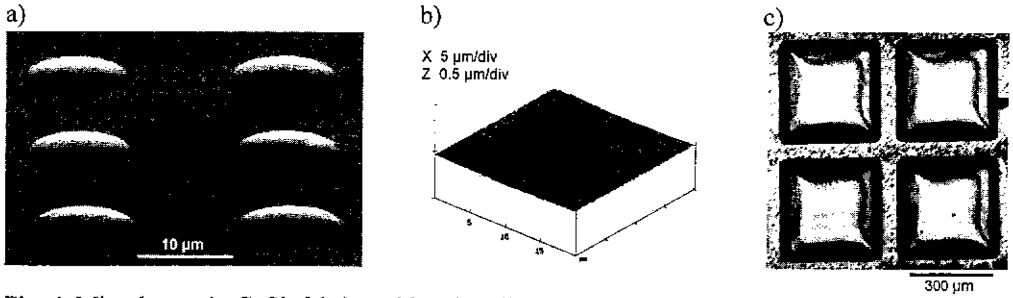

Fig. 4. Microlenses in GaSb fabricated by photolithography and Ar/O_2 sputter etching: a) SEM and b) AFM images of 10 μm circular microlenses, c) optical photograph of 300×300 μm square microlenses.

Fig. 5 illustrates influence of gas flow ratio $Ar/(BCl_3+Ar)$, RF power and etching time on GaSb depth of etching in BCl_3 plasma. Fig. 6 shows SEM micrographs of circular grating distributed Bragg reflector (DBR) and portion of 100 μm length of grating region / 1.7 μm depth grating fabricated in GaSb by e-beam writing and RIE in BCl_3 plasma. Grating consisted of 0.4 μm, wide circular rings separated by 0.6 μm gaps was etched at f = 7 sccm BCl_3, p = 60 μbar pressure and P =

30 W RF power. The etching rate of GaSb in applied conditions was 350 nm/min. High selectivity in BCl_3 plasma etching of GaSb over SiO_2 and Cr mask (1:29 and 1:150 respectively) allows to obtain deep etching profiles. The etch rate of PMMA/Cr mask in CCl_4/O_2 plasma was v = 170 nm/min. and SiO_2 mask in CF_4/O_2 plasma - v = 350 nm/min.

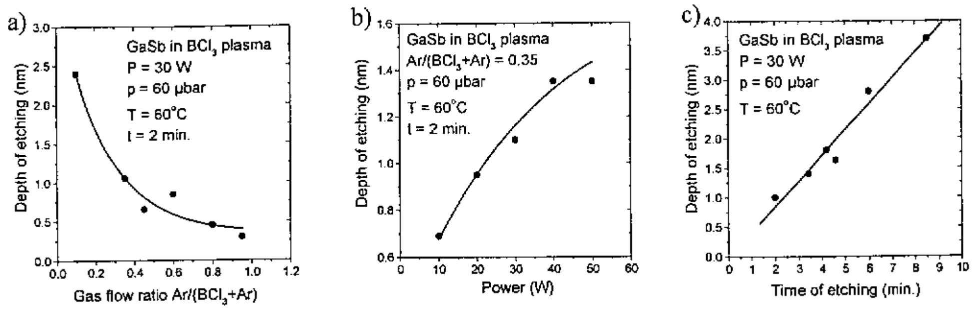

Fig. 5. Etching of GaSb in BCl_3 – based plasma. Influence of: a) gas flow ratio, b) RF power, c) etching time.

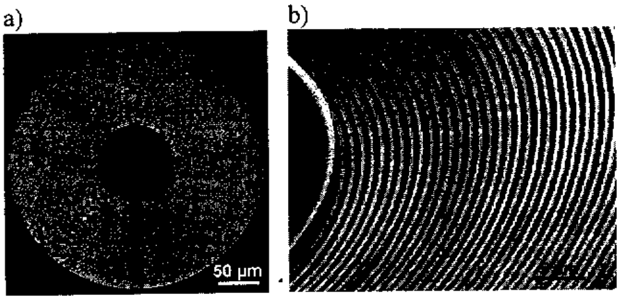

Fig. 6. SEM micrographs of GaSb circular grating fabricated by e-beam lithography and RIE in BCl_3 - based plasma.
Magnitude of a) 350x, b) 3500x.

Conclusions

Fabrication of surface-relief microstructures in GaSb has been demonstrated. Using resist reflow technique we have obtained high quality square (300×300 μm) and circular (aspect ratio height to diameter 0.4/10 μm) GaSb microlenses. E-beam lithography/RIE technique was used to pattern circular gratings (0.4 μm linewidth, 1 μm period and 1.7 μm depth) in GaSb substrate.

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