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ScienceDirect

Microelectronic Engineering 84 (2007) 1244–1247

MICROELECTRONIC ENGINEERING

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Focused ion beam modifications of indium phosphide photonic crystals

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Available online 27 January 2007

Abstract

This paper presents investigations in focused ion beam structuring and modification of indium phosphide/indium gallium arsenide phosphide based photonic crystal power splitters. The optical transmission and splitting ratio were compared to devices fabricated with electron beam lithography and inductively-coupled plasma, reactive ion etching. Prototyping of novel photonic designs, chip modifications, repair, and post-processing with focused ion beams may well reduce time to market in the telecommunication industry.

Keywords: Focused ion beam modifications; Photonic crystals; Indium phosphide

1. Introduction

Focused ion beam (FIB) structuring is a technique which allows rapid prototyping, modifications, repair and post-processing of micro-electromechanical, electronic, or optical devices in the range of tens of nanometers [1]. The required precision in geometry can be achieved during material milling by adjusting beam overlap and ion dose for each point of the structure separately. Scanning/milling strategies can be developed through trial-and-error strategies but have to be modeled for complex structures [2].

We present FIB structuring and modifications of indium phosphide/indium gallium arsenide phosphide (InP/InGaAsP) based photonic crystal (PhC) power splitters. The power splitters include a central hole in the Y-junction to reduce reflections and to increase bandwidth and output power of the arms [3]. The device performance strongly depends on the position, diameter, and depth of the hole. This makes the device attractive as a benchmark for FIB fabrication. State-of-the-art PhC structuring with FIB is already known for other materials [4]. We first thoroughly studied the sputtering behavior and reaction products of InP under bombardment of focused gallium (Ga) ions (30 keV). After that, the PhC were fabricated by electron beam lithography in combination with inductively-coupled plasma, reactive ion etching (EBL/ICP-RIE) and subsequently modified by FIB. Splitting ratio and spectral response were measured using the port-to-port end-fire technique and compared to devices fabricated with EBL/ICP-RIE only.

2. Experimental

2.1. PhC material and EBL/ICP-RIE process

The 1550 nm band waveguides consist of a 522 nm InGaAsP layer (waveguide) covered with 300 nm InP grown using metal–organic vapor phase epitaxy on a (100), S-doped (5×10^{18} cm^{-3}) InP substrate (Acrotec). In order to impact the electromagnetic fields with a PhC structure, its circular holes have to reach into the substrate down to a depth of 3 μm corresponding to the decay of the field intensity of the fundamental optical mode.

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0167-9317/$ - see front matter
doi:10.1016/j.mee.2007.01.037

Lithographic tuning [5] was applied by varying the PhC lattice constants, a, and the hole radii, r, to adjust a constant ratio $r/a = 0.31$. The scalability of the Maxwell equations allows to extend the investigated reduced-frequency range ($u = a/\lambda$) of a laser source with fixed bandwidth by fabrication of the same device with different lattice constants.

The EBL process with a RAITH150, 30 kV, and the ICP-RIE process (Plasmalab 100, Oxford Instruments) with silicon nitride (SiN_x) as hard etching mask, is described in detail in [6,7]. The ICP-RIE etching was performed using $Cl_2/N_2/Ar$ chemistry [7]. For high-quality, high aspect ratio (AR) holes the balance of the nitrogen flux in the plasma is a central parameter [8]. Holes with AR > 12 could be etched and the resulting ratio after processing was $r/a = 0.36$.

To access the PhC devices, 1.5 mm-long shallow ridge waveguides were patterned on both sides by conventional photolithography and then dry-etched on the ICP-RIE system using $CH_4/H_2/Ar$ chemistry.

2.2. FIB instrument

The micro-structure modifications were made with a dual beam FIB instrument (FEI Strata 235 DB) using Ga^+ ions (30 kV) with a current range from 1 pA to 20 nA and a resolution of 7 nm. A digital beam deflection unit allows addressing any individual pixel within the field of view for a specified dwell time to irradiate arbitrary patterns.

The shapes of milled structures were measured from scanning electron microscopy (SEM) images of cross-sections. The surface was first protected by a platinum layer deposited by ion activation of an adsorbed reactive metal–organic gas ($C_9H_{16}Pt$).

Milling was performed by physical sputtering at room temperature. It was shown that sputtering leads to In rich droplets on the surface for InP/InGaAsP if not properly considered. They are described below, and in more detail in [9].

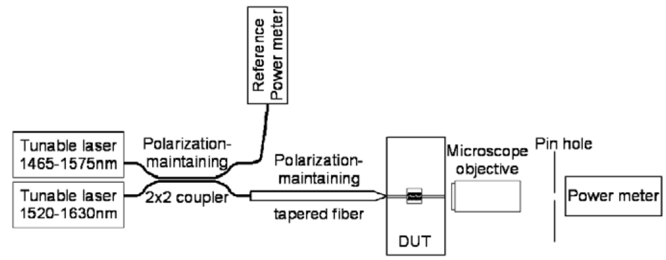

Fig. 1. Scheme of end-fire setup.

2.3. Optical setup and characterization

The optical measurements were performed with the end-fire technique [3]. Two tunable lasers, with a total wavelength range of 1470–1630 nm and 20 mW maximum output power were combined using a 2×2 coupler. One output was used for reference power measurements. The second was coupled to the device under test (DUT) via a tapered lensed fiber focusing onto a cleaved facet into the DUT. The input setup is polarization maintaining and all measurements were done with transversal electric (TE) polarization. Signal collection was done over a microscope objective to measure the DUT power throughput. To cover the full photonic band gap with the limited wavelength range lithographic tuning and appropriate scaling laws were applied (see Fig. 1).

3. FIB modifications of photonic crystals in InP

3.1. Sputtering of InP

The measured sputter yield at vertical incidence on the InP substrate was $Y = 1.27\ \mu m^3/nC$ at room temperature (Si: $0.15\ \mu m^3/nC$). However, due to selective sputtering of P, In–Ga droplets may form thereby increasing surface roughness (Fig. 2a) [9]. Milling of holes is further challenged by the fact that material is redeposited in the hole, ultimately limiting the attainable aspect ratio. Additionally, ions impinging with large angles of incidence are backscat-

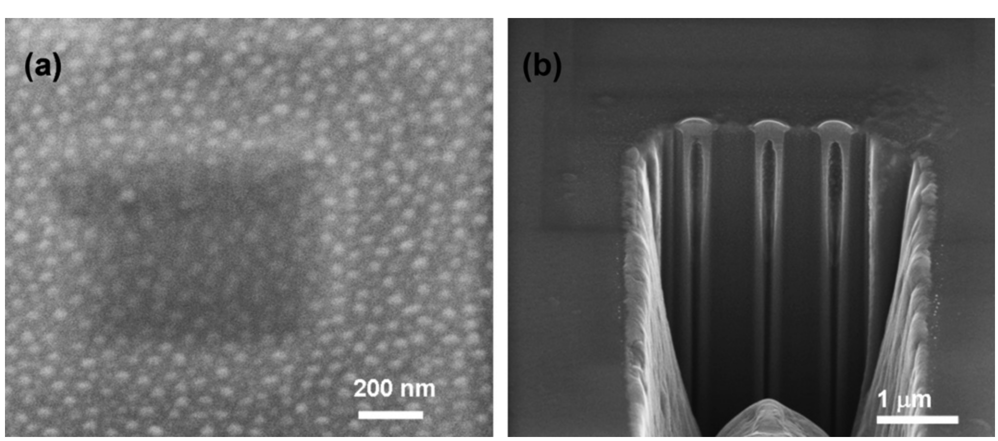

Fig. 2. (a) In–Ga islands on InP (fluence: $4.9 \times 10^{17}\ cm^{-2}$), (b) holes with AR > 4.

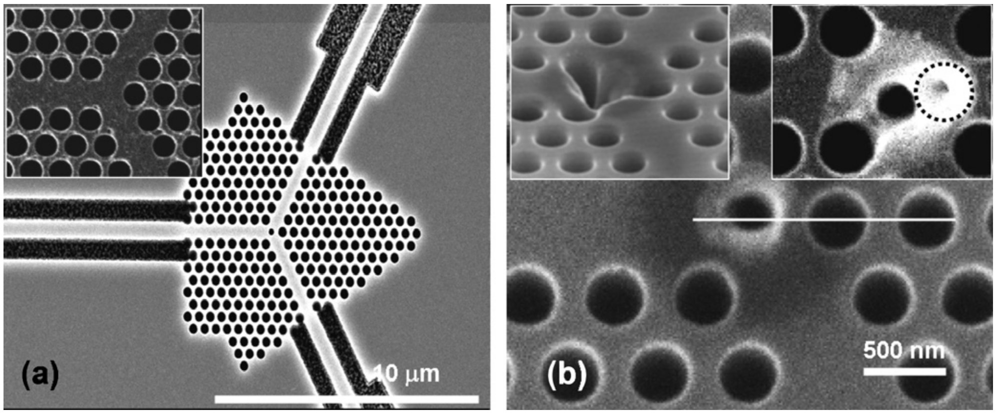

Fig. 3. (a) PhC power splitter (EBL/ICP-RIE) with and without central hole (inset), (b) FIB-fabricated central hole with offset, funnel shape (left inset), redeposition (right inset/dashed circle).

tered, especially when colliding with a heavy In atom, leading to V-shaped holes (self-focusing) [2]. We obtained AR > 4 for physical sputtering and good sidewall verticality comparable to EBL/ICP-RIE processes. Fig. 2b shows three holes protected with platinum in InP with high aspect ratio. Hole diameters ranged from 173–230 nm. Positioning of the holes was verified by SEM and is better than 60 nm.

3.2. PhC power splitter modifications

The PhC power splitters were fabricated by EBL/ICP-RIE with six lattice constants $a = 375$–500 nm, including four devices for each a. One device served as reference with the central hole fabricated by EBL/ICP-RIE. The remaining three power splitters were modified by milling the hole in the Y-junction with the following FIB processes. FIB A–C have different currents and total milling times, respectively: *A* (10 pA, 2min), *B* (10 pA, 1min), and *C* (1 pA, 5min). All holes were milled as concentric circles in sequence of their radii ending with the outmost circle. The dwell time was calculated from the desired radial fluence distribution and the effective area of each milled point taking into account the integer number of points per annulus. The dwell time profile adopted was $\sim r^{1.5}$, which was found to give the most parallel walls while alleviating ion self-focusing [2]. The hole patterns were designed with a diameter 20% smaller than the target diameter to compensate their broadening on the surface caused by the ion distribution. The number of pattern repetitions was set to reach the wanted total milling time and thus depth.

Two disturbing milling effects were observed, especially for the processes FIB A and FIB B, which are expected to influence the wave-guiding properties because the main optical mode reaches the PhC surface. Certain holes were funnel-shaped due to the ion distribution degradation with increasing space-charge effects. Others showed redeposition of sputtered material which even partially covers neighboring holes (Fig. 3b). Improvements are expected by using a suitable etchant gas, such as I_2 or Cl_2, analogous to ICP-RIE [9].

Fig. 3a shows micrographs of PhC power splitters as fabricated by EBL/ICP-RIE with and without (inset) central hole. Close-ups of FIB fabricated central holes are depicted in Fig. 3b. A central hole with offset is shown, as well as a hole with extreme funnel shape (left inset) and one with redeposition closing neighboring holes (right inset).

4. Optical characterization of PhC power splitters

The power splitters fabricated with EBL/ICP-RIE show a flat transmission over the reduced-frequency range $u = a/\lambda = 0.24$–0.32. The W1-waveguide (waveguide lacking one row of holes) cutoff is clearly visible below $u = 0.24$ [3]. Both branches show a 50–50% transmission (Fig. 4, incoupling- and outcoupling-losses are not de-embedded). The devices with a FIB-C-milled central hole show 5 dB and 20 dB lower transmissions for the lower and upper branches, respectively. A shift of the central hole (measured from SEM micrographs to be 18 and 60 nm) with respect to the input waveguide axis leads to a splitting ratio between 5 and 12 dB of the branches which varies with reduced-frequency. The variation is explained by the fact that the lith-

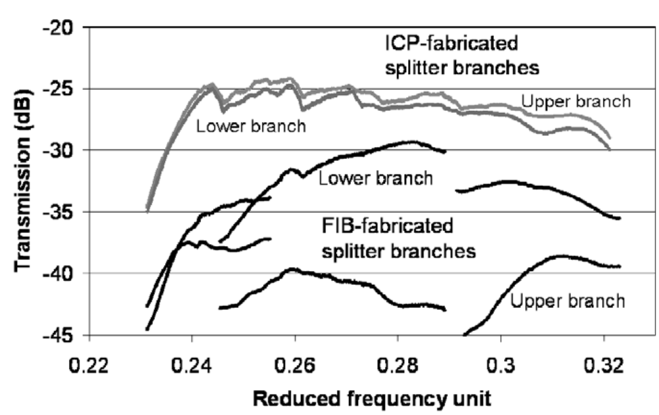

Fig. 4. Comparison of transmission: EBL/ICP-RIE only (grey), FIB-C-milled central hole with offset (black). Smoothed graphs to eliminate Fabry–Perot fringes (facet to facet cavity).

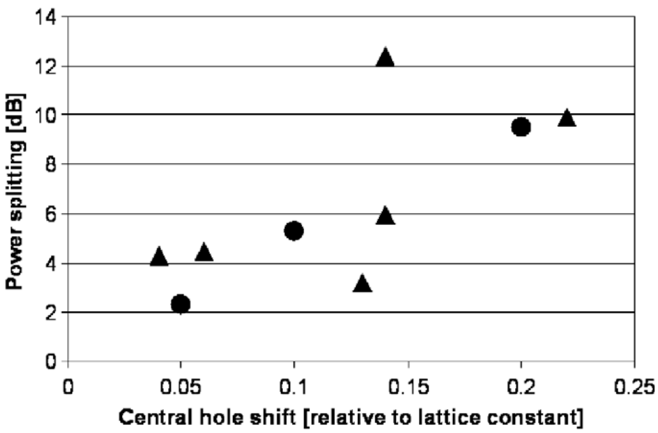

Fig. 5. Power splitting versus central hole shift: simulation (circles), measurements (triangles).

ographic tuning technique was used to cover the full bandwidth and the central hole offsets were not the same for all lattice constants. The overall lower transmission for the FIB-fabricated structures can be explained by the funnel shape of the central hole and the redeposition. Two conclusions can be drawn: (i) the power splitters fabricated using processes FIB A and B have a lower total transmission than FIB C, and (ii) the splitting ratio increases with central hole offset.

This can be used to fabricate splitters with ratios other than 50:50. Simulations (COMSOL software) with a 2D model of the PhC power splitter confirm the measurements. In Fig. 5, the power splitting versus central hole shift relative to lattice constant is plotted for the measurements (triangles) and the simulations (circles). Although effects like the funnel shape of the holes, non-circularity, and asymmetry are not considered and contribute to the scattering of the measurements, the agreement is good.

5. Conclusions

We fabricated PhC-based power splitters on InP/InGaAsP using EBL/ICP-RIE and FIB. Transmission was found to be very sensitive on the position and shape of the central hole in the Y-junction. A funnel-shaped upper part of the hole and redeposition lead to out-of-plane scattering and additional losses of up to 12 dB. Positioning accuracy of better than 10 nm is required to control the splitting ratio. Gas enhanced etching is expected to improve the FIB process with respect to the hole shape and redeposition.

Acknowledgements

For discussion and simulation: Prof. Christian Hafner and Cuidong Xui. For financing: ETH-INIT project CDM (composite doped metamaterials). For EBL/ICP-RIE processing: FIRST Center for Micro- and Nanoscience of ETH Zurich.

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