Electrochemical and Solid-State Letters, **8** (2) C30-C32 (2005)
1099-0062/2004/8(2)/C30/3/$7.00 © The Electrochemical Society, Inc.

Waveguide Structures Based on Porous Indium Phosphide

S. Langa,[a,z] S. Frey,[a,*] J. Carstensen,[a] H. Föll,[a,] I. M. Tiginyanu,[b] M. Hermann,[c] and G. Böttger[d]**

[a]*Faculty of Engineering, Christian-Albrechts University, 24143 Kiel, Germany*
[b]*LLDSS, Institute of Applied Physics, Technical University of Moldova, 2004 Chisinau, Moldova*
[c]*Walter Schottky Institute, Technical University of Munich, Am Coulombwall, D-85748 Garching, Germany*
[d]*Technical University Hamburg-Harburg, 21073 Hamburg, Germany*

We researched the possibilities for engineering the morphology of porous structures in n-InP. Lithographic patterning of the sample surface before anodic etching was shown to modify considerably the electric field distribution which, in its turn, defined the direction of pore growth inside the specimen. We show that local formation of the nucleation layer combined with the possibility to introduce current-line oriented pores in a controlled manner represents a promising tool for manufacturing waveguide structures based on porous InP. Some results on simulation of the properties of these structures are presented.

Manuscript submitted July 17, 2004; revised manuscript received September 25, 2004. Available electronically December 23, 2004.

InP is an important material for optoelectronic systems. Among other advantages, the possibility to integrate active and passive devices (*e.g.*, light-emitting diodes and waveguides) on the same substrate is decisive for further development of integrated optoelectronic circuits. Due to its relatively high refractive index, bends in devices like waveguides can be made smaller and sharper making the devices smaller and more compact.[1] Additionally, the electronic bandgap of InP (1.34 eV) is close to that of the light being used in optical communications; therefore, electro-optical effects are stronger and can be achieved in shorter distances and with lower driving voltages. However, for both passive and active devices, inexpensive processing methods are highly desired to make optoelectronic/photonic integrated circuits highly competitive. Electrochemical etching of porous structures in InP substrates can contribute essentially in this direction.[2-9]

Recently, the so called current-line oriented pores, for short curro pores, have been reported.[6] Such pores do not grow along definite crystallographic directions, as for example the macropores in Si or the so called crystallographically oriented pores in III-Vs, for short crysto pores, but always grow perpendicular to the equipotential lines in the anodized substrate.[5] From this also is derived the name of the pores. Thus, by engineering the potential distribution inside the sample it is possible to change the direction of the pores accordingly.

In this paper we show that an easy way to control the potential distribution inside an anodized sample is lithographic patterning,[5,10] *i.e.*, partially covering a sample with a mask. Lithography is extensively used in Si[11] though not to control the direction of pore growth but to define an ordered nucleation of pores. In what follows, the morphology of new structures obtained by engineering the potential distribution inside the InP sample will be presented and discussed.

(100) Oriented, S-doped, *n*-InP ($n = 3 \times 10^{18}\ \mathrm{cm}^{-3}$) wafers were used. The samples were covered with a layer of photoresist in which parallel 10 μm bright stripes were opened by standard lithography (Fig. 1a). Subsequently, the samples were anodized in 5% aqueous HCl under potentiostatic conditions (U = const.) using an electrochemical cell as described elsewhere.[6] The etching conditions were specially chosen to obtain current-line oriented pores, *i.e.*, $U = 3...9$ V in steps of 0.5 V. The etching time was between 0.1 and 1 min. After etching, the samples were investigated in cross-section and top view using a Philips XL series scanning electron microscope (SEM) functioning at 10 and 15 kV. Note that the polymer mask was intentionally not removed from the sample after etching so as not to affect the structure. Simulation of the resulting waveguide-like structures was performed using the finite difference time domain (FDTD) method.

Figures 1 and 2 show the results of the experiments carried out with samples patterned with polymer photoresist ($U = 6$ V for $t = 1$ min). Figure 1a and b show a general top overview and a magnified top view under the photoresist respectively. To see the structure under the photoresist, the accelerating voltage of the SEM

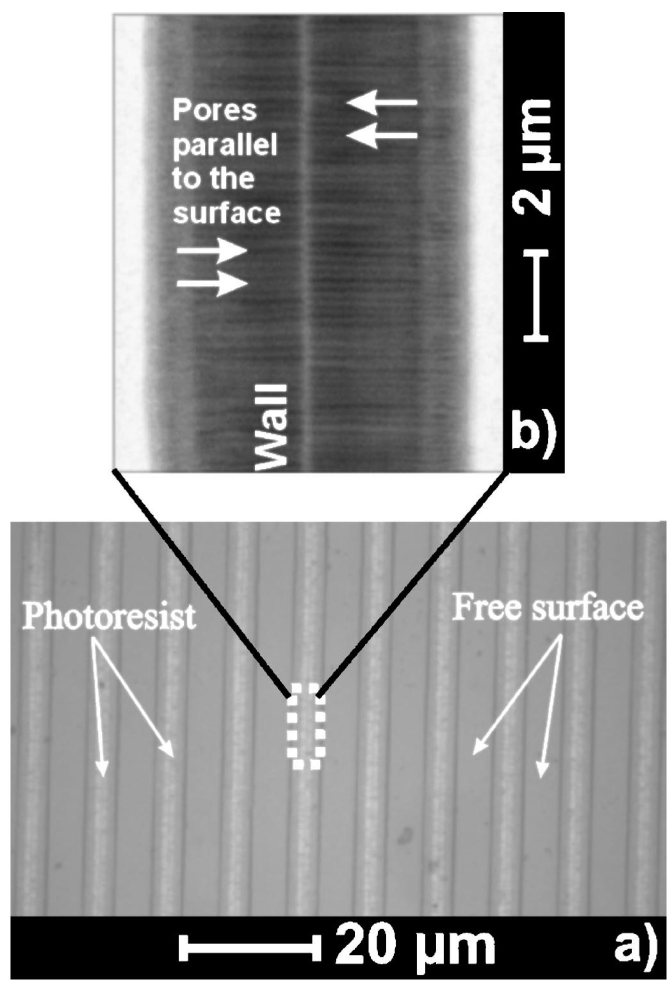

Figure 1. (a) Surface top overview. (b) Magnification of the porous morphology obtained under the photoresist.

* Electrochemical Society Student Member.
** Electrochemical Society Active Member.
z E-mail: slang1010@yahoo.com

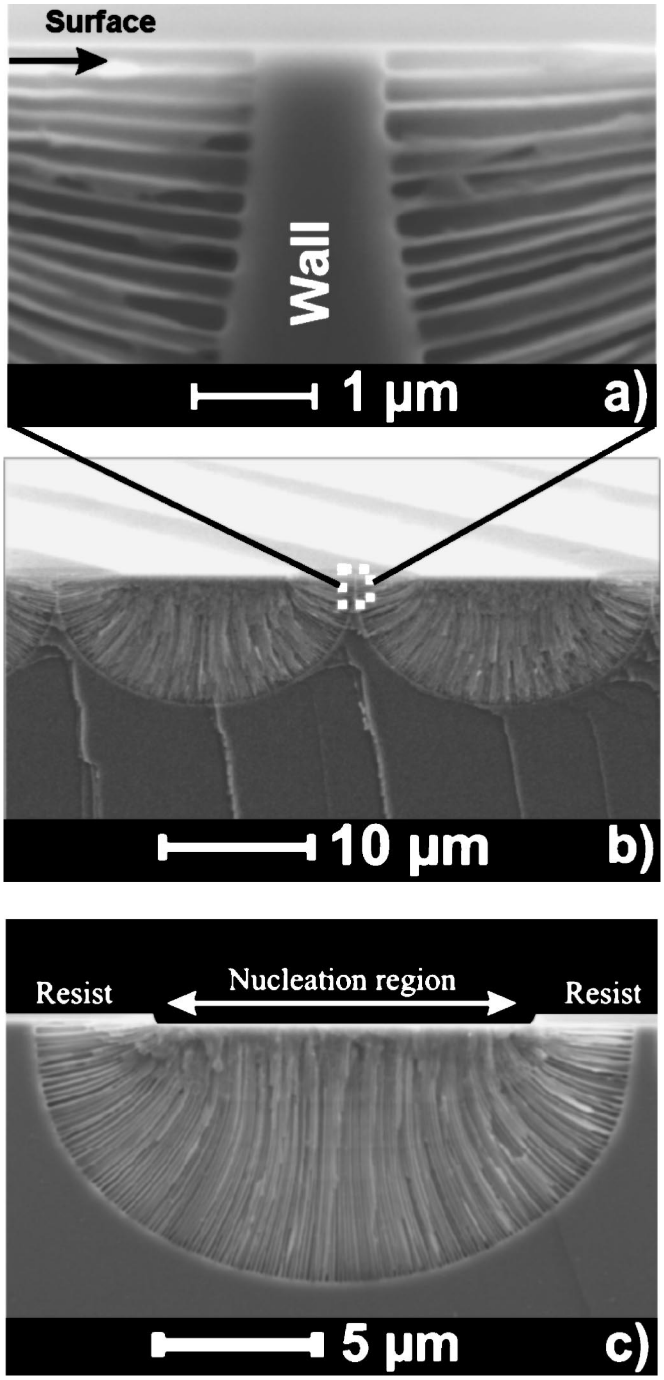

Figure 2. (a) Magnification of the structure in cross-section under the photoresist. (b) Cross section overview showing the bulk wall between two porous regions. (c) Magnification of the radially growing current-line oriented pores;

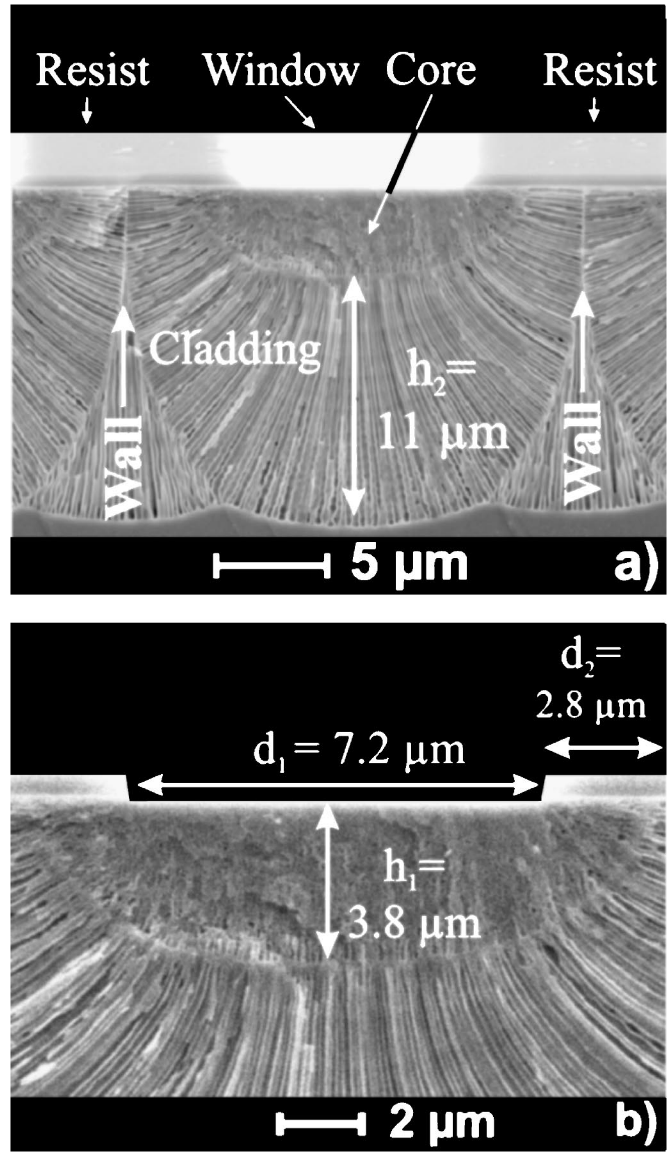

Figure 3. (a) A waveguide structure with a step-like porosity change. (b) Magnification of the low refractive index core layer.

was increased from 10 to 15 kV. Figure 2a and b show the cross-section general overview (b) and a magnified cross-section situated directly under the photoresist (a). Figure 2c shows the cross section view of a region between two stripes of photoresist.

As one can see from Fig. 2c, the pores nucleate only on the surfaces not covered by photoresist, *i.e.*, between two stripes, and grow radially, also under the photoresist, away from the nucleation region. It is evident that the pores do not expose any crystallographic characteristics of the single crystalline substrate. The direction of the pores changes gradually from perpendicular to the substrate surface (in the center of the nucleation region), to parallel to the surface (at the edges of the nucleation region, *i.e.*, near the photoresist).

The pores growing parallel to the surface are clearly visible in Fig. 1b and Fig. 2a. The radial growth of current-line pores is a conclusive proof of the fact that such pores grow perpendicular to the equipotential lines of the electric field in the anodized substrate. Making an analogy between a light wave passing through a small aperture and the current flow through a region of uncovered InP surface surrounded by two stripes of photoresist, the equipotential lines of the electric field will behave similar to the wave front of the light passing thought the aperture, *i.e.*, they will move radially outward from the slit exposing a hemispherical shape.

The bulk wall visible between the two porous regions is a hint that the current-line oriented pores cannot intersect, therefore they will stop growing or will change their direction of growth when the pore wall becomes equal to double the width of the space-charge region. This is in contrast to the crystallographically oriented pores which can intersect without changing their direction of growth.[12,13]

A careful analysis of Fig. 2a and c reveals that the diameter of the pores increases slightly as the pores grow deeper into the substrate (or under the photoresist). In this way, the degree of porosity of the layer involved increases as well. Considering the porous layer as an effective medium with a porosity-dependent refractive index, it is straightforward to conclude that the (effective) refractive index of the porous structure will decrease as the porosity increases. As a result, a gradient in the refractive index in the depth of the structure is obtained. Recently, layers exposing a porous gradient have been proposed as waveguidelike structures in Si.[14] However, in InP such structures are much more desirable taking into account the necessity for developing new optoelectronic integrated circuits mentioned in the introduction of this article.

A more pronounced difference in the degree of porosity and thus in the refractive index is shown in Fig. 3. In this case, a layer of crystallographically oriented pores is first formed with a low porosity and then the radial growth of the current-line oriented pores is allowed (higher porosity). The low porosity layer can be considered to be the core whereas the current-line oriented pores are the cladding layer of a waveguide-like structure.

Taking into account that the porosity of porous layers made of crystallographically oriented pores is not higher than 15%, and that the layers containing current-line oriented pores are at least two times as porous, a rough approximation results in the refractive index of the core and cladding layers presented in Fig. 2 as high as 15 and 30%, respectively from the refractive index of bulk InP ($n = 3.1$). Consequently, it is reasonable to take the refractive index of the core to be $n_{\mathrm{core}} = 2.5$, whereas that of the cladding is $n_{\mathrm{cladding}} = 2.0$.

The simulations performed using the FDTD method show that the waveguide-like structure with the dimensions presented in Fig. 3 is a multi-mode waveguide for the optical communication frequency $f = 200$ THz ($\lambda = 1500$ nm), the effective refractive indices for different modes being closely spaced. According to our simulations, to obtain a single-mode waveguide for the same wavelength and with the same porosity, the dimensions of the structure should be scaled down as follows: $d_1 = 0.5\ \mu\mathrm{m}$, $d_2 = 1\ \mu\mathrm{m}$; $h_1 = 0.5\ \mu\mathrm{m}$, and $h_2 = 1.5\ \mu\mathrm{m}$. However, in this case the evanescent field can go deep into the cladding ($n = 2$) layer, thus eventually coupling over to the InP bulk substrate. To avoid such problems, it is necessary to make the cladding layer (h_2) much thicker.

In conclusion, the pores in InP prove to exhibit a high flexibility in their manner of growth. By exploiting this flexibility it is possible to obtain structures suitable for different applications in photonics and optoelectronics. The most promising features are the self arrangement of the curro pores in a long range order,[8] the switching from curro to crysto pores resulting in the formation of Bragg-like structures[5] and the possibility to surround a high refractive index by a low refractive index porous layer giving rise to a waveguide structure. Proper design and optimization of the characteristics of such structures could make them ready for integration in various optoelectronic circuits.

Acknowledgments

This work was supported by the Deutsche Forschungsgemeinschaft (DFG) under the grants 436 MOL 113/2/0-1 and FO 258/4-1.

Christian-Albrechts University assisted in meeting the publication costs of this article.

References

1. E. Koteles, *WDM Solutions*, **3**, 25 (2001).
2. E. Kukino, M. Amiotti, T. Takizawa, and S. Arai, *Jpn. J. Appl. Phys., Part 1*, **34**, 177 (1995).
3. H. Fujikura, A. Liu, A. Hamamatsu, T. Sato, and H. Hasegawa, *Jpn. J. Appl. Phys., Part 1*, **39**, 4616 (2000).
4. A. Liu and C. Duan, *Physica E (Amsterdam)*, **9**, 723 (2001).
5. H. Föll, S. Langa, J. Carstensen, M. Christophersen, and I. M. Tiginyanu, *Adv. Mater. (Weinheim, Ger.)*, **15**, 183 (2003).
6. S. Langa, I. M. Tiginyanu, J. Carstensen, M. Christophersen, and H. Föll, *Electrochem. Solid-State Lett.*, **3**, 14 (2000).
7. S. Langa, J. Carstensen, I. M. Tiginyanu, M. Christophersen, and H. Föll, *Electrochem. Solid-State Lett.*, **4**, G50 (2001).
8. S. Langa, I. M. Tiginyanu, J. Carstensen, M. Christophersen, and H. Föll, *Appl. Phys. Lett.*, **82**, 278 (2003).
9. H. Tsuchiya, M. Hueppe, T. Djenizian, and P. Schmuki, *Surf. Sci.*, **547**, 268 (2003).
10. G. Su, Q. Gu, and R. E. Palmer, *J. Appl. Phys.*, **94**, 7598 (2003).
11. A. Birner, R. Wehrspohn, F. Müller, U. Gösele, and K. Busch, *Adv. Mater. (Weinheim, Ger.)*, **13**, 377 (2001).
12. V. P. Bondarenko, A. F. Dorofeev, and N. M. Kazachits, *Microelectron. Eng.*, **28**, 447 (1995).
13. S. Langa, J. Carstensen, M. Christophersen, H. Föll, and I. M. Tiginyanu, *Appl. Phys. Lett.*, **78**, 1074 (2001).
14. J. Charrier, E. Le Gorju, L Haji, and M. Guendouz, *J. Porous Mater.*, **7**, 243 (2000).