Indium Phosphide Planar Integrated Optics Comes of Age

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For planar integrated optics, the future has finally arrived

Integrated optics had its start in the sixties, when scientists observed that light could be guided and steered by thin films. The first big commercial success of integrated optics occurred in the next decade, with the development of low-loss optical fiber. This invention was responsible for a giant leap in capacity in the mid-eighties, when fiber cables started to replace copper cables in the telecom network.

Planar lightwave circuits (PLCs), where flat layers (rather than the cylindrical core found in fibers) guide light, stayed on the sidelines. Although capable of higher optical signal processing functions beyond mere transport, PLCs did not find a mass market. More expensive than the electronic alternatives, they were confined mostly to niche markets and laboratory applications for the early part of the fiberoptic revolution.

In the last decade, however, the explosive growth in internet traffic has brought a bandwidth boom, and a critical need to manage huge volumes of information. Enter wavelength-division multiplexed (WDM) photonics, where many color-coded signals co-propagate in the same medium. WDM has caused a second giant leap in communications capacity. Planar integrated optics components, with their ultrafast capability for routing and processing of optical signals, have finally been pressed into service. Demand for many optical components now exceeds supply.

Indium Phosphide: Adapting Form to Function

PLCs can serve many roles in fiberoptic networks: splitting and combining of signals, sorting of different wavelengths, modulation, switching between space channels, monitoring, filtering, amplifying, and grooming (i.e., the reshaping and retiming of optical signals). Many materials can be used for the passive functions such as filtering and splitting. However, for generation and detection of light in

the 1200 – 1600 nanometer fiberoptic region of the spectrum, the current material of choice is indium phosphide.

When compared with the sophistication of modern silicon ICs, state-of-the-art indium phosphide photonic integrated circuits are still in their infancy, with several orders of magnitude less complexity. Nevertheless, indium phosphide PLC manufacturers must develop a similar set of standard microfabrication, mass production, and packaging techniques. Smaller, faster, cheaper and more functional photonic integrated circuits are needed in order to achieve wide systems deployment and compete in the technology marketplace.

Some of the challenges to material science are already apparent with the simplest possible circuit, a straight rib waveguide. Figure 1 shows a typical result of reactive ion etching (RIE) of indium phosphide with chlorine. Although “dry” ion etching is much more controllable than wet etching with chemical solutions, the level of surface roughness shown can cause unacceptable scattering loss and a high variability in device parameters.

Sharp Splits, Smooth Curves

One of the keys to high-quality mass production is standardization of fundamental components. A basic building block for indium phosphide photonic circuits is the multimode interference (MMI) coupler. MMI couplers (such as that shown in Figure 2) are used in interferometric modulators and wavelength filters. MMIs are also employed in power splitters, like the 1 X 8 depicted in Figure 3. The fact that indium phosphide circuits are able to confine light very tightly proves advantageous for the operation characteristics of MMI devices. Numerical simulations based on the Time/Frequency Domain Simulator for Photonic Devices (TFDS),[1] which takes into account both reflection and scattering effects, demonstrate that sharply defined, vertical sidewalls are essential for accurate spectral response and power splitting in MMI structures. To develop a fast, highly controllable RIE method yielding deep, vertical sidewalls and smooth morphology, it is necessary to move beyond simple etch chemistries. This is often a painstaking process, as illustrated by the series of experimental results in Figure 4.

Chemistry is Key

Process engineers control the quality and speed of RIE by varying conditions such as ion energy, gas flow, temperature and pressure, and especially the gas composition. For example, fast etching of indium phosphide - several microns per minute-has been achieved with mix of chlorine and argon[2]. High-speed etching is a necessity for high-throughput production. However, the requirements of smooth surfaces or straight sidewalls might call for quite different recipes.

The quest for the perfect profile involves a balancing act between physical and chemical effects[3]. Chemical etching occurs when an etchant bonds with an indium or phosphorous on the sample, and the resulting molecule is whisked away in the gas. Since indium and phosphorous would not generally enter the same set of reactions, this could cause an uneven surface like that shown in Figure 1. On the other hand, physical effects include brute-force sputtering, which can knock off chunks of material and kick out leftover etching by-products. Clean up mechanisms during RIE, both physical and chemical, are important. If by-products are allowed to accumulate near the sample, they can slow down the etch, form their own masking layer, and cause irreproducible results.

The series of photos in Figure 4 shows how the balance between physical and chemical etching affects waveguide quality. In Figure 4a, the hourglass shape is a typical chemically-etched profile. Material has been removed from the sides as well as the top, severely undercutting the silicon dioxide mask. However, by changing the relative proportions of gases in the mix, chemical etching can be suppressed. Figures 4b and 4c show successively straighter sidewalls as the physical etching component is increased. Etching occurs primarily from the top, and the integrity of the mask is maintained. Although the etch rate does slow down somewhat, the etch rate for the rib in Figure 4c is a still-respectable one micron per minute.

Advanced Nanostructures Meet their Market

In recent years, progress in dry etching has made possible entirely new types of semiconductor materials and devices. These include photonic-bandgap crystals, micro-electromechanical structures (MEMS), ultra-narrow gap directional couplers (Figure 5) and extremely tight radius bends (Figure 6). However, such feats of fabrication are no longer regarded as laboratory curiosities or gee-whiz demonstrations. With the growth in the number of WDM channels and the extension of fiberoptic networks closer to the home, there is intense pressure to develop cost-effective, mass-produced PLC components and subsystems. Ultra-precise processes such as the ones discussed here are already being incorporated in the manufacture of current integrated circuits. Nanostructures will be critical to the development of the next decade's communications infrastructure, and will certainly play a role in the next great leap forward in telecommunications capacity .

FIGURES

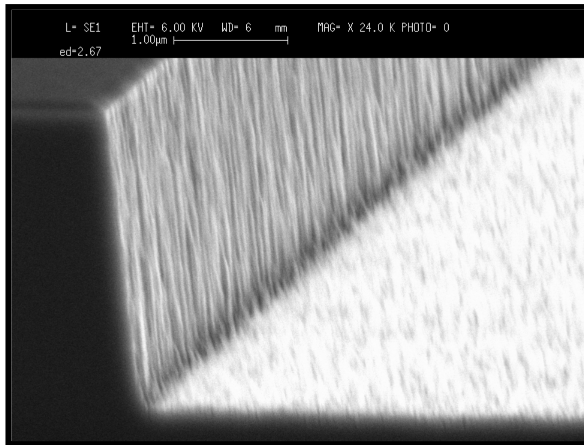

Figure 1 Scanning electron micrograph of an indium phosphide waveguide etched using conventional methane/hydrogen reactive ion etching displays edge roughness on the sidewall.

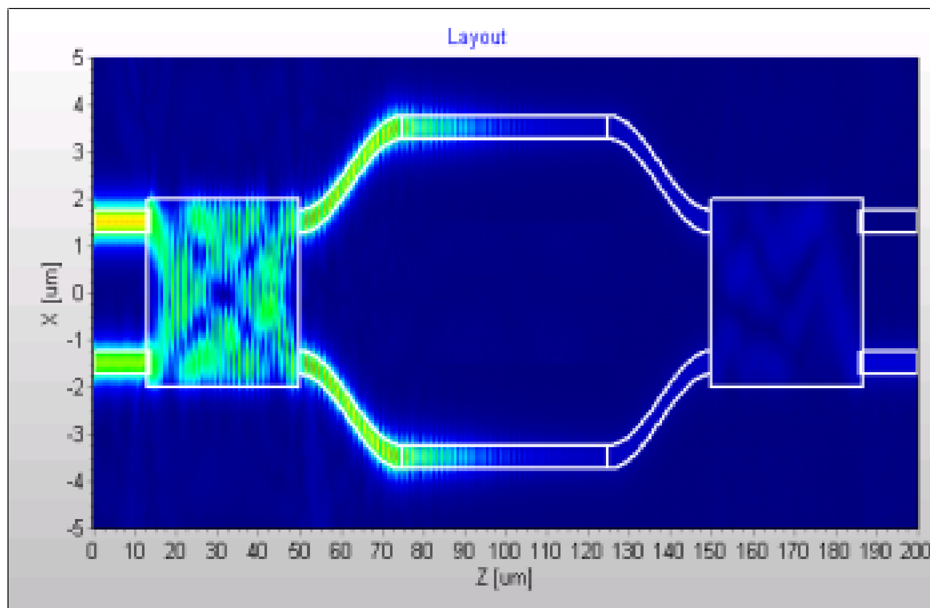

Figure 2 Optical intensity pattern within an electroabsorption modulator, relying on two multimode interference couplers (rectangular boxes) to split and recombine a light wave fed in at the top left. A voltage applied to the two arms in the center determines which path the light takes. Calculated via Apollo Photonics' Time/Frequency Domain Simulator For Photonic Devices (courtesy of David Rajcak).

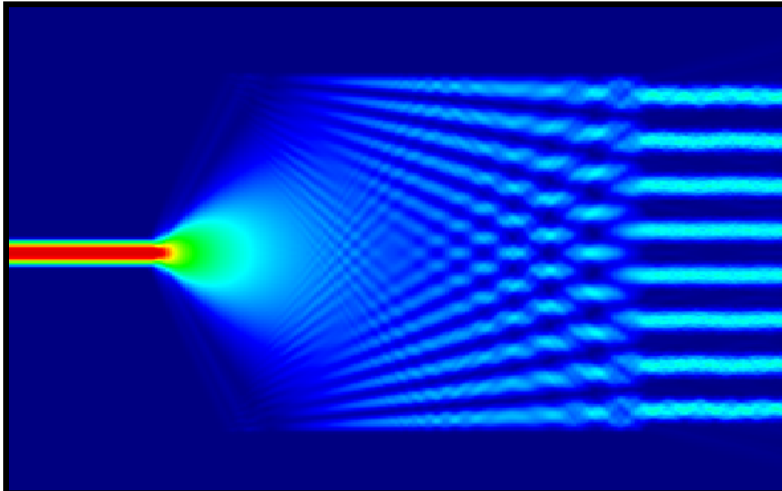

Figure 3 Optical Intensity Pattern within a 1X8 Multimode Interference Splitter (simulation courtesy of Jose Jimenez).

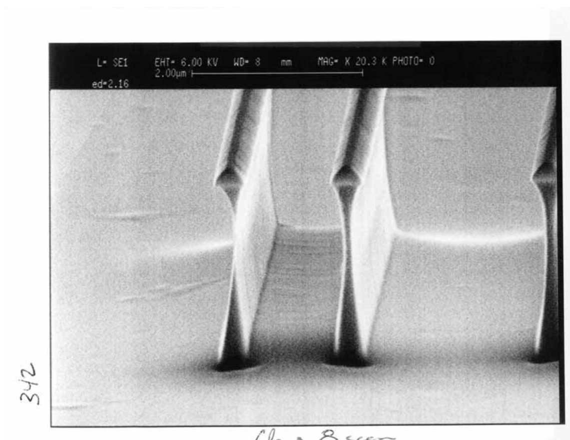

Figure 4a Scanning electron micrograph of indium phosphide rib waveguides displays an isotropic profile and mask undercut, characteristics of an RIE process that is dominated by chemical rather than physical mechanisms.

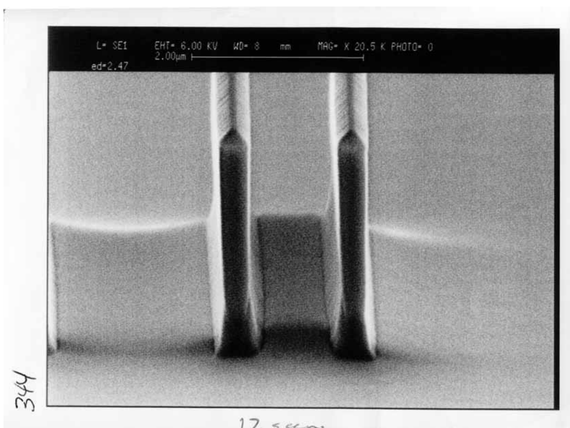

Figure 4b As the relative flow of etchant gases is tuned toward physical etch conditions , a bell-bottom shape persists but attack from the sides is suppressed.

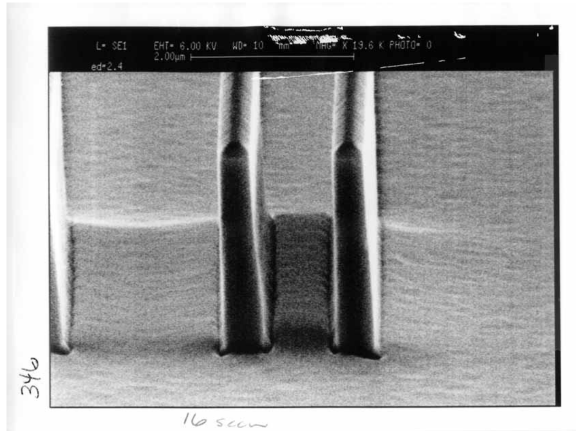

Figure 4c Further tuning of the gas mix results in straight sidewalls, characteristic of an anisotropic physical etching process that is primarily vertically-directed.

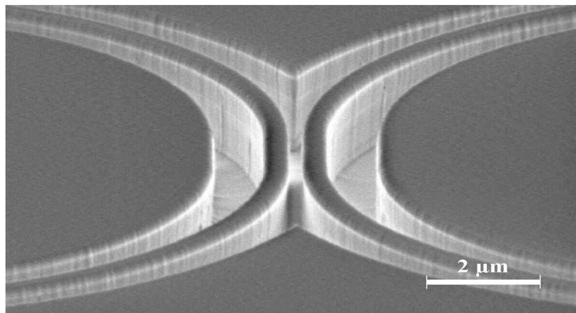

Figure 5 Deeply-etched directional indium phosphide coupler structure produced at Nanovation Technologies. The minimum separation between waveguides is 0.25 micron.

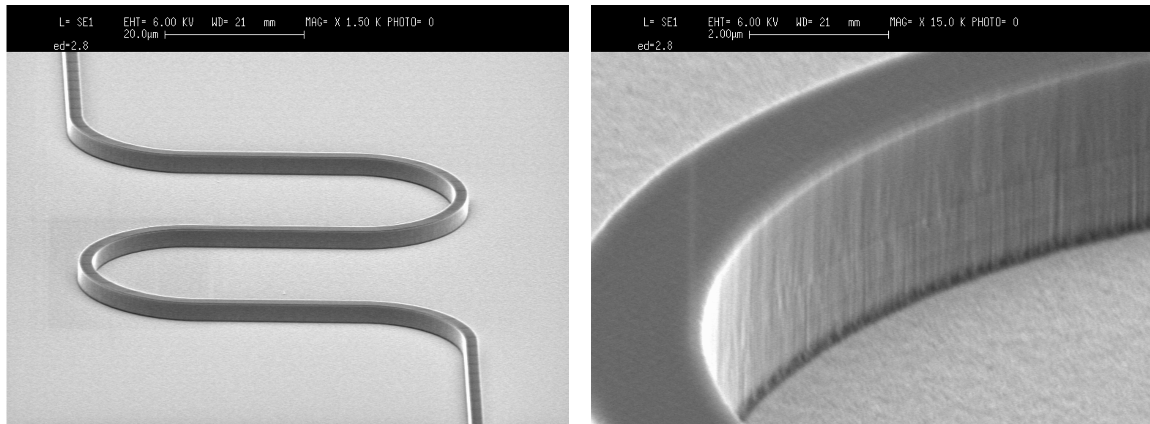

Figure 6 Indium Phosphide meander waveguide structure produced at Nanovation Technologies by e-beam lithography and inductively coupled plasma reactive ion etching process. At right, magnified view of etched waveguide surface.

REFERENCES

[1] A demonstration copy of the TFDS simulator can be downloaded from Apollo Photonics website at http://www.apollophoton.com.

[2] "Electron cyclotron resonance plasma etching of InP through-wafer connections at >4 micron per minute," Y. W. Chen et al, J. Vac. Sci. Technol. B18(4), p.1903 (2000).

[3] "Microscopic modeling of InP etching in CH4-H2 plasma," L. Houlet, J. Vac. Sci. Technol. A 17 (5), p. 2598 (1998).