The manufacture of optical components on 4-inch InP in a GaAs production fab

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Abstract

Optical components including multi-wavelength 1310-nm InAlGaAs DFB lasers and high-speed mesa-based PIN and APD photodetectors have been fabricated on 4-inch InP using standard production tools in a GaAs manufacturing facility. There have been few published reports on optical components fabricated on InP substrates of this size. The use of production GaAs toolsets and processes for optical component fabrication are shown to have important device cost, yield and performance advantages.

INTRODUCTION

This paper presents the results of a three-year-long program at TriQuint Semiconductor Texas to fabricate InP-based lasers and detectors using a production GaAs electronics fab. The objective was to produce optical components with high yield and low cost using established GaAs manufacturing equipment and processes. Although these optical components are not currently in production, the lessons learned from this development process are particularly important and relevant in the current environment of consolidation and cost reduction in the optical component industry. This trend was recently highlighted in the 2005 Communications Technology Roadmap (CTR) coordinated by the Massachusetts Institute of Technology [1]. The aim of this report was to develop a roadmap for the optical-communication semiconductor industry similar to the successfully implemented roadmap of the silicon electronics industry. Among the key recommendations of this study were for optical component suppliers to move to an outsourced manufacturing model due to the high costs of maintaining an internal production facility, and for an industry-wide effort to develop new optical component manufacturing processes and standardized design rules. Our experience at TriQuint Semiconductor effectively demonstrates the important yield, process capability and cost advantages that are possible by leveraging an existing III-V electronics-manufacturing infrastructure.

DEVICE TECHNOLOGIES

Devices that were fabricated at TriQuint-Texas include uncooled 1310-nm InAlGaAs ridge-waveguide λ/4-phase-shifted distributed feedback (DFB) lasers, mesa-based 10 and 40GB/s InGaAs PIN photodiodes (on InP as well as metamorphic GaAs substrates) and 10-GB/s InAlAs APD photodiodes. The use of ridge waveguides with phase-shifted DFB gratings and mesa-based photodiode device architectures were specifically targeted for their potential to enhance device yield and uniformity and for their ability to exploit TriQuint's manufacturing strengths. For example, phase-shifted DFB gratings can enable single-mode laser yields close to 100% and greatly reduce the need for costly device screening and testing at the chip level. To fabricate phase-shifted DFB gratings generally requires high-resolution electron beam lithography, an established volume production process at TriQuint Semiconductor. As for photodetectors, mesa architectures for high-speed PIN and APD photodiodes necessitate accurate control of doping profiles during epitaxial growth and proper mesa sidewall passivation to minimize dark current, but they eliminate the need for low-yielding and non-uniform diffusion processes.

MATERIAL

Base epitaxial material for both lasers and detectors was grown in-house by MBE on 4-inch InP substrates, while MOCVD was used for epitaxial regrowth over the grating-patterned DFB base structures. Valved cracker sources for arsenic (As_4) and phosphorus (P_2) and growth temperatures from 500-560 ºC were used to obtain excellent uniformity and In(Al)GaAs/InGaAsP material quality. PL wavelength uniformity across the 4-inch substrates (with an edge exclusion of 5 mm) was better than 3 nm, comparable to or better than typical results on 2-inch material. It should be noted that the MIT report highlighted the need to migrate towards larger, 4-inch InP substrates for optical circuits as die sizes will eventually grow with increasing levels of integration. There have been very few published reports to date of optical device performance on InP substrates of this size, particularly for DFB laser diodes.

MESA-BASED PHOTODETECTORS

Figure 1 shows a SEM micrograph of a fabricated mesa-based PIN photodiode. The device fabrication was very similar to existing process production process flows used to build HBT devices at TriQuint Texas. As shown in Figure 1, connection to the p-type contact was made using an electroplated airbridge structure, which is not commonly used for PIN detector fabrication. Ti-Pt-Au and Au-Ge-Ni were used for the p- and n-type contact metallizations, respectively. The mesa was formed using a citric-acid-based wet etch. One of the important challenges in fabricating mesa-based photodetectors (and APD photodiodes in particular) is the minimization of dark current resulting from leakage current paths due to surface states at the exposed mesa sidewall. A combination of polyamide and silicon nitride was used to passivate the mesa structure and maintain dark currents in the nA range.

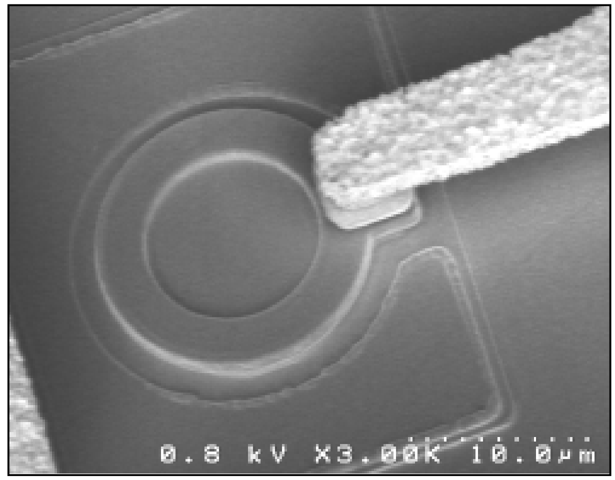

Fig 1. SEM micrograph of a PIN mesa-based photodetector.

Figure 2 shows the frequency response of a 40-GB/s mesa-based PIN photodetector grown on a metamorphic GaAs substrate. The 3-dB bandwidth is greater than 35 GHz with a responsivity of 0.65 A/W. PIN photodiodes were fabricated on both InP and metamorphic GaAs substrates with similar performance. However, the use of a metamorphic substrate, which leveraged previous experience with metamorphic pHEMT growth, enabled novel growth variations used to optimize the device structure for higher sensitivity. The responsivity of 0.65 A/W is the highest we have seen for a 40GB/s mesa photodetector and is competitive with performance from waveguide PIN detectors, which are much more difficult to couple to optical fibers than mesa detectors. More than 50,000 device-hours of accelerated life testing at 125 °C/5V were accumulated on the passivated PIN diode structures without degradation in dark current performance.

Shown in Figure 3 is set of responsivity curves for a 10GB/s mesa-based avalanche photodiode. The detector operates at voltages less than 20 V, which is much lower than diffused junction APDs which generally operate at biases of 40 V or more. The use of an epitaxially grown mesa structure provides excellent control over the thickness and charge of the multiplication region of the device. Similar performance can be achieved from diffused junction APDs (though at higher operation voltage), but only with very low device yields due to the difficulty in controlling the diffusion depth to the very tight tolerances required.

III-V compound semiconductor substrates are known for their fragility compared to Si, and InP substrates in particular are even more brittle than GaAs. An important consideration for low-cost manufacturing of InP-based optical components, therefore, is to assess the robustness of 4-inch InP substrates in a production environment. The wafer fab at TriQuint Texas undergoes routine stress testing of all wafer handling equipment in order to identify problematic tools and minimize breakage of GaAs substrates. No particular accommodations were made in this project, however, to adapt these systems to InP wafers. A total of 59 4-inch semi-insulating InP photodetector wafers were processed through the GaAs production line. The aggregate breakage rate was 13 %, although differences were noted across substrates from different vendors and in some cases breakage as low as 7 % were observed. It is likely that a combination of improved wafer handling procedures and working with substrate vendors can further improve InP wafer breakage yields.

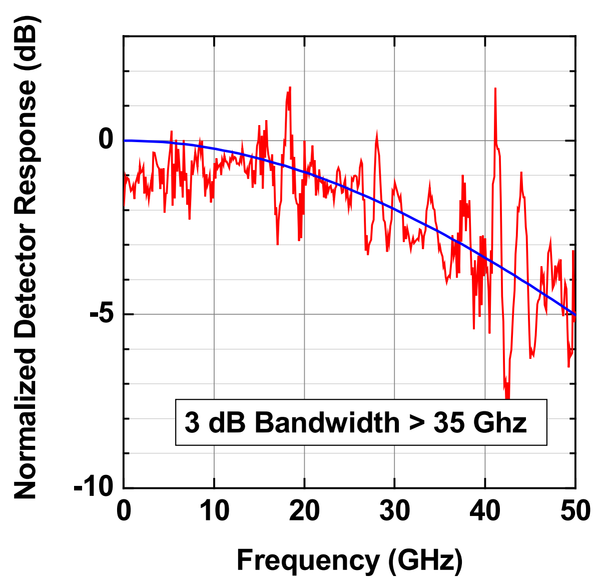

Fig 2. Frequency response of a metamorphic 40-GB/s mesa-based pin photodetector with a responsivity of 0.65 A/W.

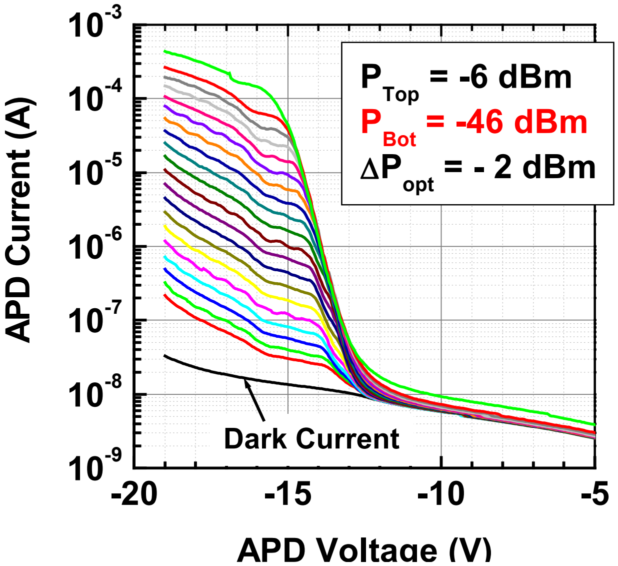

Fig. 3. Responsivity curves for a 10GB/s low-voltage (<20 V), mesa-based avalanche photodetector.

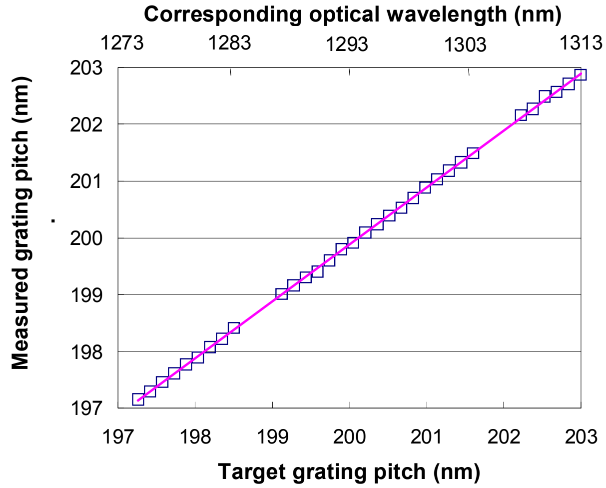

Fig. 4. Measurements of grating pitches patterned by electron-beam lithography. The standard deviation of the variation from targeted pitch is less than 1 Å.

DFB LASERS

The DFB grating structures were patterned in the InGaAsP etch-stop layer (immediately above the active region of the device) by electron beam lithography using an Hitachi HL 800-D with high speed resist. The slow throughput (as well as high capital costs) of writing dense grating patterns has traditionally represented an obstacle to implementing electron beam lithography for DFB laser production. The Hitachi lithography tool at TriQuint Texas is designed for high throughput with a shaped beam that can pattern each grating period in a single "shot". Combined with the high resist sensitivity, the cycle time for a 4-inch wafer containing more than 60,000 laser diodes was typically 45 minutes to 1 hour. With this throughput, a reasonable volume of DFB wafers can be supported within existing production utilization of this lithography tool.

Electron beam lithography provides significant advantages over conventional, holographically-patterned gratings for DFB lasers. Producing stable, single-mode operation is one of the primary yield-reducing factors in DFB lasers, which can be as low as 50-60% when patterned with standard uniform gratings. The insertion of a single $\lambda/4$ phase shift in the center of the grating greatly enhances modal stability. We have consistently measured single-mode yields greater than 95% from several thousand devices in multiple fabrication runs. This high yield was also maintained when using asymmetric gratings (with the $\lambda/4$ phase shift positioned off-center) designed to shift as much as 70% of the optical power to one output facet.

Another important capability of direct-write lithography is the ability to pattern specific and multiple grating wavelengths on a single wafer. Figure 4 shows a graph of measured versus target grating period for 31 average-pitch gratings patterned across a wafer. The top x-axis maps the corresponding wavelength of laser operation for each grating pitch in the 1310-nm space (these are calculated laser wavelengths, not measured); similar results have also been demonstrated for 1550-nm gratings. The standard deviation of error in grating period accuracy is better than 1 Å, which represents extraordinary dimensional control. The ability to pattern numerous different grating pitches on a single wafer with this level of accuracy is a powerful enabling technology for optical component fabrication.

An SEM micrograph of a fabricated InAlGaAs DFB laser diode is shown in Figure 5, while a high-magnification cross-sectional view of the ridge is visible in the figure inset. The ridge was formed using a self-aligned process in which the evaporated Ti-Pt-Au p-type contact metallization served as an etch mask to pattern the underlying InGaAs cap layer. An HCl-H_3PO_4 wet etch then formed the ridge structure by etching through the p-type InP cladding layer down to an

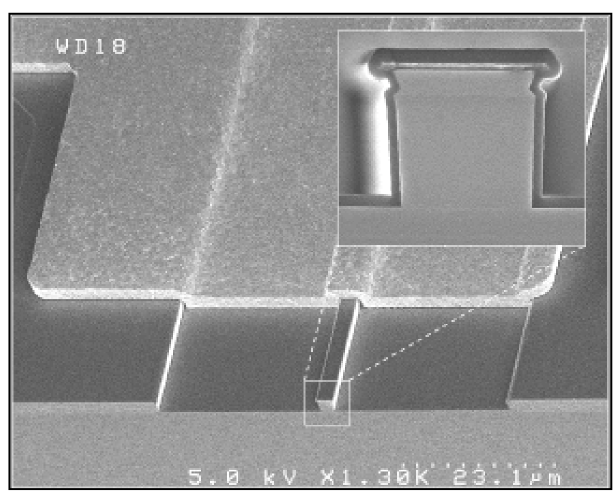

Fig. 5. SEM micrograph of a 1310-nm ridge DFB laser diode.

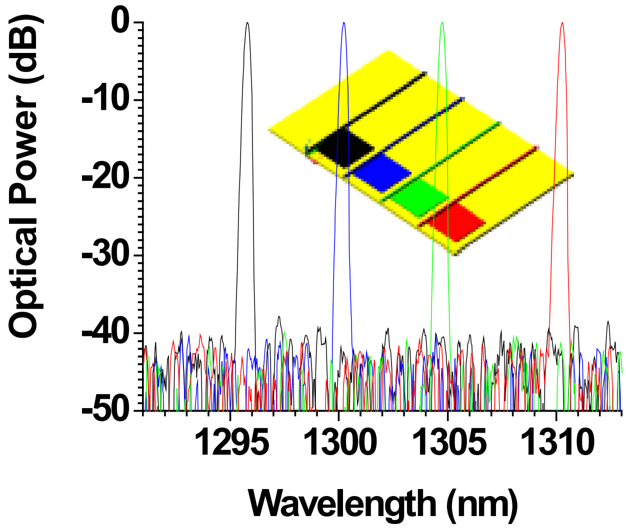

Fig. 6. DFB laser spectra from four laser diodes fabricated with different wavelengths on a single substrate.

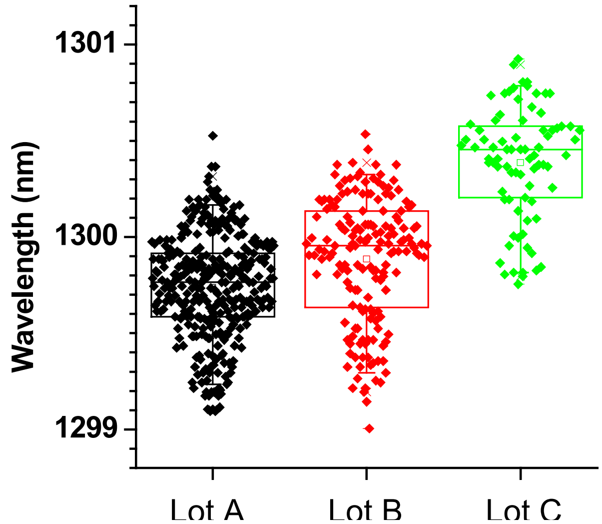

Fig. 7. Box plot demonstrating wavelength control for DFB lasers in three separate fabrication runs. The standard deviation of wavelength was better than 1.8 Å intra-wafer and 3.5 Å across three lots.

InGaAsP etch stop layer. This wet etch has the useful characteristic that it is constrained in the lateral dimension by the InGaAs cap layer as well as the vertical, and will not undercut even if overetched, thereby enabling excellent dimensional control of the ridge width. A layer of compressive silicon nitride with a thickness of either 200 or 800 nm was deposited over the ridge; the thicker nitride layer was used for high-speed (10 GHz) device operation. An electroplated Au bond pad contacted the top of the ridge. The substrates were then ground to a thickness of 100-nm, and an evaporated Ti-Pt-Au metallization formed the backside n-type contact.

Figure 6 shows measured DFB spectra of four laser devices operating at different wavelengths fabricated on a single wafer. Typical device performance characteristics included I_{th} = 20mA, V_{on} = 1V, SMSR greater than 40dB, To = 94K and output power of 10 mW. With an asymmetric grating the output power could be increased by as much as 70 %. As noted previously, with an 800-nm thick nitride layer the device bandwidth was greater than 10 GHz for I_{th} + 60 mA. More than 50,000 device-hours were accumulated under accelerated life tests at 85 °C/150 mA without degradation.

Figure 7 exhibits the wavelength uniformity for devices measured across the 4-inch wafers for three different devices runs. The intra-wafer wavelength uniformity was better than 1.8 Å, while among three process runs the standard deviation was less than 3.5 Å. This demonstrates exceptional control of not only the grating fabrication but also the epitaxial material growth.

CONCLUSIONS

PIN photodetectors and DFB lasers have been fabricated on 4-inch InP substrates with high performance, yields and reliability. All device processing including material growth, with the exception of laser facet antireflection coating, was carried out using GaAs production equipment at TriQuint Semiconductor Texas. The utilization of this manufacturing environment provided several important advantages. The wide range of production process capabilities, including electron beam and stepper lithography, PVD (compressive silicon nitride, evaporated and sputtered metallizations) and electroplating played an important role in producing devices with high yield and performance. Device cost is estimated to be very competitive due to the larger substrate sizes, high yields, and perhaps most importantly, through leveraging available capacity on existing high-volume production toolsets and systems.

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REFERENCES

[1] MIT Microphotonics-Center Industry Consortium Communications Technology Roadmap, http://mph-roadmap.mit.edu, May 2005.

ACRONYMS

DFB: Distributed feedback
APD: Avalanche photodiode
HBT: Heterojunction bipolar transistor
pHEMT: pseudomorphic high electron mobility transistor
PIN: p-type – intrinsic – n-type
PL: Photoluminescence