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Thick orientation-patterned growth of GaP on wafer-fused GaAs templates by hydride vapor phase epitaxy for frequency conversion

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ABSTRACT

Quasi-phase-matched (QPM) GaP layers up to 300 μm thick have been produced by low-pressure hydride vapor phase epitaxy (LP-HVPE) overgrowth on orientation-patterned GaAs (OPGaAs) templates fabricated using a wafer-fusion bonding technique. The growth on the OPGaAs templates resulted in up to 200 μm thick vertically propagating domains, with a total GaP thickness of 300 μm. The successful thick growth on OPGaAs templates is the first step towards solving the material problems associated with unreliable material quality of commercially available GaP wafers and making the whole process of designing QPM frequency conversion devices molecular beam epitaxy free and more cost-effective.

1. Introduction

Nonlinear optical frequency conversion is an effective technique for generating high-power infrared (IR) and terahertz (THz) wavelengths, which are not readily available from existing direct laser sources. Such novel laser sources can have applications for various military and commercial applications. Frequency conversion devices (FCDs) based on birefringent materials or QPM ferroelectrics are commercially available. However, problems like thermal lensing damage and large walk-off angle in birefringent materials and strong IR absorption in QPM ferroelectrics have led to the search for alternatives. For IR sources based on QPM, orientation patterned (OP) GaAs has emerged as the front runner due to its high nonlinear coefficient $d_{14} = 170$ pm/V, good thermal conductivity (52 W/m-K), and a wide transparency range [1,2]. GaAs has proven to be effective at generating wavelengths of interest using QPM where a two-step process of an OPGaAs template fabrication (by sub-lattice inversion technique using MBE) and a subsequent thick HVPE overgrowth is employed [3–6]. As an alternative to sub-lattice inversion technique, wafer-fusion bonding is shown to be an efficient and less expensive technique for developing OPGaAs templates [7]. While OPGaAs devices have many advantages for nonlinear frequency conversion, efficient pumping from visible and near-IR wavelength laser sources is not feasible due to its large two-photon absorption (2 PA).

As an alternative, OPGaP offers some important advantages over OPGaAs, especially its lower 2 PA. GaP also has a wide IR transparency range (0.6–11 μm), high thermal conductivity (110 W/m-K), and a good nonlinear coefficient ($d_{14} = 71$ pm/V at 1.064 μm). These advantages motivated the design of the first FCD based on stacks of GaP wafers with alternating polarity [8]. The preparation of OPGaP templates by sub-lattice inversion MBE, similar to the approach for producing OPGaAs templates, has been recently demonstrated [9,10]. The epitaxial growth of periodic GaP structures on OP templates by HVPE has also been demonstrated by our group [11,12]. Compared to OPGaAs, the template fabrication and HVPE growth of OPGaP still has a lot of work. Overcoming some of the limitations, our group has demonstrated both the fabrication of OPGaP templates using wafer fusion bonding technique and the successful overgrowth on these templates [13]. However, commercially available GaP wafers often possess low crystalline and surface quality compared to GaAs. As a result, OP templates produced by either wafer-fusion bonding or MBE have a high

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number of defects and have poor reproducibility. To overcome the wafer quality issues, we have developed an HVPE process for thick growth of OPGaP on OPGaAs templates. This allows us to use established high quality OPGaAs templates, which are more consistent and more economical than GaP.

Furthermore, the required domain period, Λ_{QPM} for first order QPM depends on the wavelengths (λ's) of the interacting pump (p), signal (s) and idler (i) waves and on the wavelength-dependent refractive indices of material (n's) as follows:

$$\frac{1}{\Lambda_{QPM}} = \frac{n_p}{\lambda_p} - \frac{n_s}{\lambda_s} - \frac{n_i}{\lambda_i}, \quad (1)$$

The reciprocal relationship between Λ_{QPM} and the refractive index in Eq. (1) dictates that the lower the refractive index is (GaP has a lower refractive index than GaAs) the wider is the domain period. Using published parameters for GaAs [14] and GaP [15], the tuning curves for OPGaAs and OPGaP at a pump wavelength of 1.06 μm for optical parametric oscillators (OPO) show that the QPM GaP domain widths are wider than those of GaAs and hence more practical to achieve good domain fidelity in the latter case when growing millimeter thick structures [13]. The OPO tuning curves for OPGaP at three different pump wavelengths are shown in Fig. 1.

2. Template fabrication and OPGaP growth

OPGaAs templates used for this work are fabricated by wafer-fusion bonding process utilizing GaAs (100) on-axis wafers. The wafer-fusion process was first demonstrated by our group for OPGaAs structures [7,16] by bonding GaAs wafers with 1 μm GaAs and 0.5 μm AlGaAs layers epitaxially grown by MBE. The AlGaAs layer has been used as an etch stop layer. Later this wafer-fusion approach was extended to GaP [13] and was proven to be robust for follow-up thick HVPE regrowth. To simplify the process further, the OPGaAs templates used in this work were fabricated without the use of the GaAs/AlGaAs MBE layers.

The fusion process steps are as follows. Two GaAs (100) wafers are first cleaned with solvents and while immersed in methanol the wafers are assembled face to face with proper alignments. The wafer pair is then placed between graphite shims and inserted into a custom made graphite fixture. The fixture is slid into a thick wall quartz tube, which is then introduced into a tube furnace with a controlled nitrogen purge flow. As the temperature of the fixture is gradually raised to 700 °C, the expansion of the graphite fixture is suppressed by the quartz tube, thereby applying a compressive force to the wafer pair and fusing them together. Upon successful fusion, the top GaAs wafer of the fused pair is thinned down to within 10 μm of the bonding interface using mechanical lapping and polishing. This process is followed by further polishing the top surface until approximately 5 μm of the top wafer remains with smooth surface morphology. Optical images of one of the fused pair after lapping and polishing are shown in Fig. 2. This is a successful demonstration of wafer-fusion of full 2-inch wafers without any visible defects across the whole wafer.

At this point, photolithography is used to transfer the grating pattern with the desired domain periods onto the top wafer. ICP dry etching is then used to etch into the bottom GaAs wafer to reveal the alternate crystallographic orientations. More details of the fabrication steps are given in Refs. [13,16], where wafer-fusion was achieved using smaller size samples. Further analysis of the template by scanning electron microscope (SEM) imaging of the top surface revealed some etch damage (Fig. 3) while the cross-section showed no voids or defects at the interface (Fig 3).

The HVPE growth was performed in a horizontal hot-wall quartz reactor customized for a low-pressure operation. The applied substrate temperatures were in the range of 715–750 °C. The reactor pressure was below 10 Torr. Relatively low V/III ratios in the range 2.00–2.5 and supersaturation levels between 0.5 and 1.0, were used in this work. Further details of the HVPE growth of GaAs and GaP materials are reported elsewhere [7,11,12]. The HVPE growth was performed on plain (100) on-axis wafers to figure out the optimal growth conditions for the 3.5% lattice mismatched layers. After obtaining successful growth on plain wafers, growth on OPGaAs templates was initiated using the same growth conditions.

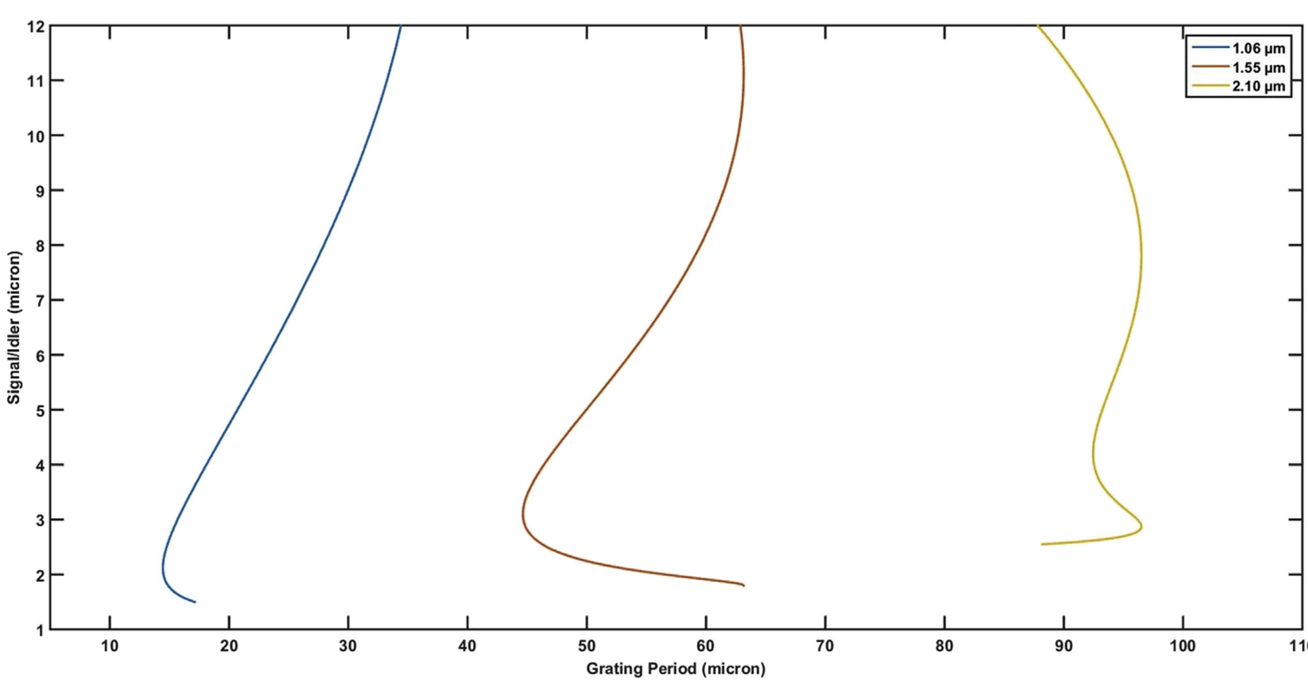

Fig. 1. OPO tuning curves for OPGaP at three different pump wavelengths.