MICROSTRUCTURED SEMICONDUCTORS FOR MID-INFRARED NONLINEAR OPTICS

Abstract. Microstructured semiconductors patterned with regions of different crystallographic orientations can be used to quasi-phasematch nonlinear interactions. This chapter reviews the fabrication, properties, and applications of these materials.

Keywords: Nonlinear optical materials; mid-infrared; frequency conversion; quasi-phase-matched; semiconductors; orientation-patterned gallium arsenide GaAs.

1. Introduction

Since its practical inception in the 1990s, quasi-phasematching (QPM) in periodically-poled ferroelectrics has proven to be a very useful technique for bulk and guided-wave quadratic nonlinear optical devices [1, 2]. One fundamental issue limiting the use of oxide ferroelectrics is their multi-phonon absorption, which generally limits their use to interactions involving wavelengths shorter than 4–5 µm. Practical application of non-oxide ferroelectrics has not been possible, so alternative materials systems suitable for QPM in the mid-infrared are of interest.

The zincblende semiconductors, such as GaAs, ZnSe, and GaP, have large nonlinear susceptibilities, low optical absorption, and transparency well into the mid-IR, and so have long been used for mid-IR nonlinear optics. However, their optical isotropy, a consequence of their cubic crystal structure, precludes birefringent phasematching, which has severely limited the applicability of these materials. A number of QPM techniques based on stacks of crystal plates with alternating orientation have been explored, but fabrication has proved to be challenging, again limiting their applicability [3, 4]. More recently, epitaxial growth of orientation-patterned materials, with lithographically controlled patterns, has greatly opened the range of applicability of these materials.

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The best developed of these materials is orientation-patterned GaAs (OP-GaAs), which has been fabricated in both thin-film (microns) and thick-film (up to \( \sim 1 \text{ mm} \)) form, suitable for guided-wave and bulk devices, respectively. Among the device results reported to date are optical parametric oscillators (OPOs) tunable from 2.1–11 \( \mu \text{m} \), an optical parametric generation (OPG) device producing a continuum from 4–11 \( \mu \text{m} \), THz generation with 3% quantum efficiency, and a single-frequency difference frequency generation (DFG) source tunable from 7.4–9 \( \mu \text{m} \).

Section 2 is an overview of the properties of zincblende semiconductors, emphasizing GaAs and including the interesting polarization effects that result from the linear optical isotropy and the high symmetry of the nonlinear susceptibility. In section 3, fabrication methods for microstructured zincblende semiconductors are discussed. Emphasis is given to all-epitaxial, lithographically controlled approaches. Section 4 describes bulk QPM device results in 43 \( \mu \text{m} \) materials, and Section 5 is a summary including future directions for research.

### 2. Properties of zincblende semiconductors

Table 1 shows key material properties for selected zincblende semiconductors. They share several intrinsic properties that make them attractive for mid-IR nonlinear optics. Essential for mid-IR operation are their low phonon energies, which lead to long-wavelength multi-phonon absorption edges and allow operation beyond 10-\( \mu \text{m} \) wavelengths. The large nonlinear susceptibilities (in the case of GaAs, approximately four times larger than \( d_{33} \) of LiNbO\(_3\)) is particularly important for mid-IR interactions, where the basic wavelength scaling of quadratic

<table>
<thead>
<tr>
<th>Material</th>
<th>Transparency Range (( \mu \text{m} ))</th>
<th>Refractive Index(^1)</th>
<th>( d_{ij} ) (pm/V)(^2,3)</th>
<th>Thermal Conductivity (W/m-K)</th>
<th>( dn/dT ) (10(^{-4} \text{K}^{-1} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>0.9–17</td>
<td>3.34</td>
<td>107</td>
<td>52</td>
<td>2.9</td>
</tr>
<tr>
<td>GaP</td>
<td>0.5–11</td>
<td>3.03</td>
<td>45</td>
<td>110</td>
<td>1.2</td>
</tr>
<tr>
<td>ZnSe</td>
<td>0.5–20</td>
<td>2.44</td>
<td>25</td>
<td>19</td>
<td>0.7</td>
</tr>
<tr>
<td>LiNbO(_3)</td>
<td>0.4–4.5</td>
<td>2.13(^4)</td>
<td>23</td>
<td>4.6</td>
<td>0.4(^4)</td>
</tr>
</tbody>
</table>

\(^1\) At room temperature, 2 \( \mu \text{m} \) wavelength.

\(^2\) \( d_{ij} \) is \( d_{14} \) for all entries except for LiNbO\(_3\), which is \( d_{33} \).

\(^3\) Nonlinear coefficient is scaled using Miller’s rule to doubling of \( \lambda_f = 2 \mu \text{m} \).

\(^4\) Refractive index and thermo-optic coefficient given for extraordinary wave of LiNbO\(_3\).