High-Reflectivity Dual-Band Bragg Mirrors Grown by MBE on Si(111) Substrates for the Atmospheric Transmission Windows Between 4 – 5 μm and 6 – 12 μm

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We show dual-band Bragg mirrors for the mid-infrared consisting of BaF_2 and PbTe grown by molecular beam epitaxy (MBE) on Si(111) substrates. The mirrors exhibit broad stop bands near the atmospheric windows between 4 – 5 μm and 6 – 12 μm with reflectivities of at least 95 %. The Si substrate easily enables device processing of the mirrors in order to fabricate tunable narrow band pass Fabry-Perot filters for the mid-infrared. The measured spectra are in good agreement to transfer matrix simulations of the whole structures indicating the high quality of the dual-band Bragg mirrors.

Introduction

The mid-infrared (MIR) spectral region covering the wavelength range between 2 and 30 μm is of enormous importance as it contains the fundamental fingerprint absorption bands of almost all poly-atomic molecular species of interest. Consequently, the MIR is very attractive for the development of optoelectronic devices such as lasers, detectors and filters for gas sensing applications. Such devices enable, e. g., dynamic exhaust gas analysis in automotive industry by detecting NO, CO and CH_4. They are also used for medical diagnostics by analyzing C isotopes in exhaled air or by detecting endogenous NO and CO in breath as an indicator of diseases (for a review see, e. g., Ref. [1]). In addition, there are atmospheric transmission windows between 3 and 5 μm as well as between 8 and 14 μm enabling free space optical communications and thermal imaging.

For such applications, high-reflectivity Bragg interference mirrors are important tools for fabrication of, e. g., narrow band pass filters. However, to access the whole wavelength range of the atmospheric windows, the stop bands of such mirrors have to be very broad. Therefore, we employed the material combination of PbTe and BaF_2 being transparent in this spectral region and exhibiting an exceedingly large difference in refractive index. As a consequence, not only a much smaller number of Bragg mirror pairs is required to obtain high reflectivities, but also the required very large stop band width can be achieved.

Here, we show PbTe/BaF_2 dual-band Bragg mirrors grown by molecular beam epitaxy (MBE) on Si(111) substrates exhibiting broad stop bands near the atmospheric windows between 4 - 5 μm and 6 - 12 μm. The Si substrate easily enables device processing of the mirrors in order to fabricate tunable narrow band pass Fabry-Perot filters for the mid-infrared.

Experimental

Structure and Design

The combination of PbTe and BaF_2 yields a very high refractive index ratio of 3.8 at a wavelength of 6 µm. This index contrast is about a factor of 3 larger than what can be achieved with the typically used III-V semiconductors (see, e. g., Ref. [2]) and leads to a large relative stop band width $\Delta\lambda/\lambda$ of 79 % for a standard Bragg mirror. However, it is still not possible to cover the whole spectral range of the two atmospheric windows.

Therefore, we employed the concept of dual-band mirrors with additional $\lambda/4$ phase shifting layers (for details see Ref. [3]). The mirrors were designed by transfer matrix calculations using the exact dispersion of the optical constants of PbTe as determined by Fourier-transform infrared (FTIR) spectroscopy of reference layers. Several dual-band mirror structures were fabricated in a IV-VI semiconductor molecular beam epitaxy (MBE) system on Si(111) substrates. Due to the mismatch in lattice-type, lattice constant (19 %) and thermal expansion coefficients (a factor of 10) between PbTe and Si, the total growth thickness is rather limited in order to achieve a reasonable quality of the mirrors. Thus, the number of mirror periods has to be kept as low as possible.

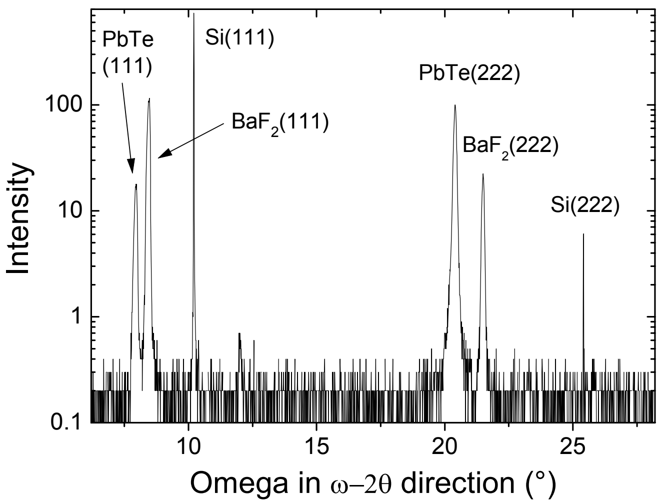

Fig. 1: X-ray ω–2Θ scan of a dual-band Bragg mirror consisting of BaF_2 and PbTe grown by MBE on Si(111) substrates .

Results

As is seen by the x-ray ω–2Θ scan in Fig. 1, the growth on Si(111) substrates of the PbTe/BaF_2 dual-band mirror structures yields fully strain-relaxed layers only with (111) orientation, as desired. The Fourier-transform infrared (FTIR) reflectivity spectra of two different structures both optimized for a minimum total thickness (3.1 µm and 3.6 µm, respectively) are shown in Fig. 2. The dual-band 1 structure (top) exhibits stop bands from 4.2 to 5.6 µm and 6.3 to 10.9 µm both with reflectivities in excess of 95 % despite its low number of layers. A slightly thicker structure (dual-band 2) (bottom) also results in two high reflectivity bands, this time even broader (3.8 – 4.6 µm and 6.4 – 12.3 µm). The spectra of both samples show a very good agreement to transfer matrix simulations of the whole structure indicating the high quality of the mirror structures.

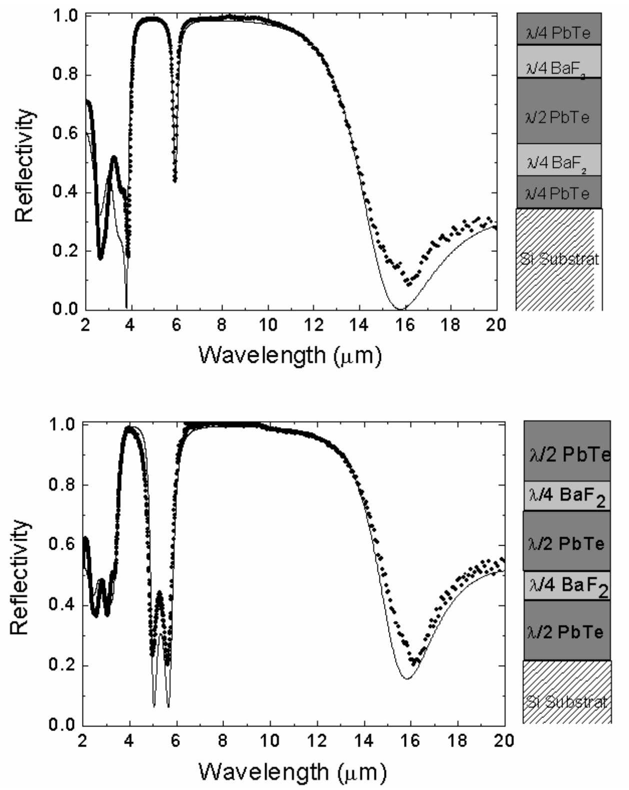

Fig. 2: FTIR reflectivity spectra (dots) of two types of dual-band Bragg mirrors consisting of BaF_2 and PbTe grown by MBE on Si(111) substrates (top: dual-band 1, bottom: dual-band 2). Both structures are sketched on the right-hand side of the spectra. The measured spectra are in good agreement to transfer matrix simulations of the whole structure shown as a line.

Conclusion

Our work demonstrates that dual-band PbTe/BaF_2 Bragg mirrors with broad stop bands in the mid-infrared spectral region can be grown by MBE in high quality on Si(111) substrates for use in tunable Fabry-Perot narrow-band filters. Such filters can be used for various sensing applications in the spectral range of the two atmospheric windows.

Acknowledgements

Financial support from the InfraTec GmbH, Germany and the Austrian Science Fund FWF, Austria is gratefully acknowledged.

References

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