Mid-Infrared High Finesse Microcavities based on IV-VI Semiconductor/BaF_2 Broad Band Bragg Mirrors

T. Schwarzl, M. Eibelhuber, W. Heiss and G. Springholz

Institut für Halbleiter- und Festkörperphysik, Johannes Kepler Universität, A-4040 Linz, Austria

We report on molecular beam epitaxially grown high-reflectivity broad band Bragg mirrors for mid-infrared devices using IV-VI semiconductors and BaF_2. This material combination exhibits a high ratio between the refractive indices of up to 3.5, leading to a broad mirror stop band with a relative width of 75%. To verify the high quality of the PbEuTe/BaF_2 Bragg mirrors, we study a half-wavelength microcavity formed by mirrors with only three periods. The resonance of the microcavity has a narrow line width of 5.2 nm corresponding to a very high finesse of 750. From this, a mirror reflectivity higher than 99.7% is deduced, in good agreement to transfer matrix simulations.

Introduction

High-reflectivity Bragg interference mirrors with almost zero absorptive losses are of great importance for advanced optoelectronic devices such as vertical-cavity surface-emitting lasers. These interference mirrors consist of pairs of dielectric layers with quarter wavelength thicknesses and different refractive indices. Epitaxial Bragg mirrors grown by molecular beam epitaxy (MBE) generally exhibit a much higher quality compared to those produced by conventional evaporation. This is due to the excellent control of the growth process and layer thicknesses, the smooth and abrupt heterointerfaces and the extremely low levels of unintentional impurities, resulting in negligible stop-band absorption [1]. However, to achieve very high mirror reflectivities with a reasonable number of layer pairs, Bragg mirror materials with as large as possible refractive index contrasts are required [1], [2]. On the other hand, for MBE the crystal structure as well as lattice parameters of the involved materials should be as close as possible in order to obtain a good structural and electronic quality of the layers, which is of crucial importance, e. g., for subsequent growth of the active material of laser structures.

In the present work, we have employed MBE grown high reflectivity broad band Bragg mirrors for infrared device applications, combining the narrow band gap IV-VI semiconductors with the dielectric material BaF_2. This material combination exhibits an exceedingly large difference in refractive index, with corresponding index ratio about a factor of 3 larger than that achievable with III-V semiconductors [3]. As a consequence, not only a much smaller number of Bragg mirror pairs is required to gain reflectivities above 99%, but also a very large stop band width can be achieved.

We successfully demonstrate PbEuTe/BaF_2 Bragg microcavities for the mid-infrared with very high finesse values, thus evidencing the very high reflectivity of the three-period Bragg mirrors of at least 99.7%. The mirrors with a very high refractive index ratio of 3.5 exhibit a very broad stop band with a relative width of 75%. The mid-infrared region is particularly important for gas spectroscopy applications, as most molecular gases have strong absorption lines in this spectral region [4].

Experimental

Structure and Design

The Bragg mirrors and microcavities were designed by transfer matrix calculations using the exact dispersion of the optical constants of the individual layer materials as determined by Fourier-transform infrared (FTIR) spectroscopy of reference layers. The structures were all grown by MBE onto (111) BaF_2 substrates. The growth temperature was 380 °C and the growth rate was 1.1 µm/h for all layers. The Bragg mirrors forming the microcavity consist of three periods of $Pb_{0.92}Eu_{0.08}Te/BaF_2$ quarter-wave layers designed for a wavelength of 3.9 µm. The half-wavelength cavity layer between the mirrors also consists of $Pb_{0.92}Eu_{0.08}Te/BaF_2$, thus being optically transparent at the design wavelength. All samples were characterized by room temperature FTIR reflectivity and transmission measurements.

Results

To verify the high quality of our $PbEuTe/BaF_2$ Bragg mirrors, first we study a half-wavelength microcavity formed by these mirrors. From the finesse or quality factor of the cavity, we can accurately evaluate the mirror reflectivity. Figure 1 shows the reflectivity spectrum of the cavity sample measured at room temperature (dots). One can see the very broad mirror stop band with almost 100 % reflectivity between 3 µm and 6 µm. On both sides of the stop band pronounced interference fringes from the total thickness of the structure appear. The relative mirror band width $\Delta\lambda/\lambda_0$ is about 75 %, where λ_0 is the central wavelength of the mirror stop band. This is due to the very large refractive index ratio n_1/n_2 between the used mirror materials $Pb_{0.92}Eu_{0.08}Te$ and BaF_2 of 3.5. Both the refractive index ratio and the stop band width are not only among the largest for MBE grown Bragg mirrors, but also for Bragg mirrors fabricated by other methods with less limitation on the material choice [1]. Compared to the most common III-V semiconductor Bragg mirrors [3], the refractive index ratio and the stop band width are a factor of 3 and 7 larger, respectively.

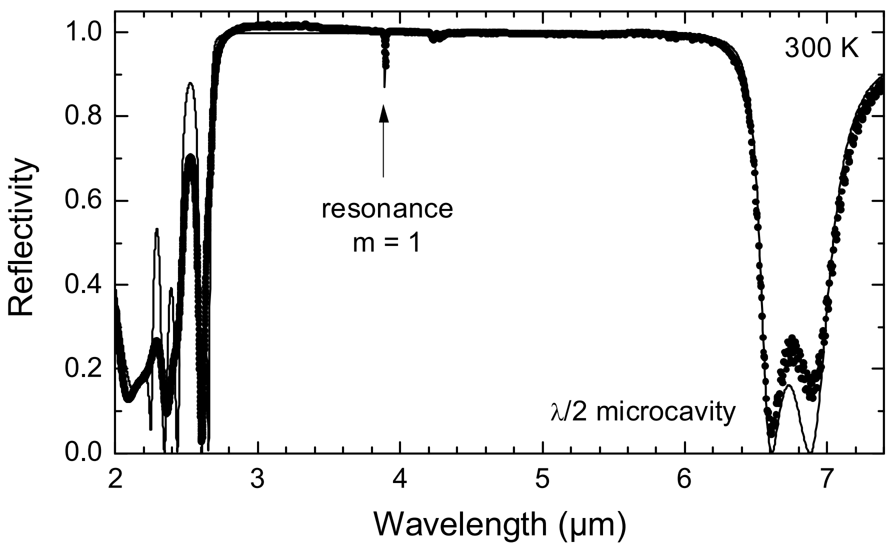

Fig. 1: FTIR reflectivity spectrum of a half-wavelength microcavity consisting of two three-period $PbEuTe/BaF_2$ Bragg mirrors measured at 300 K (dots). The corresponding transfer matrix simulation is depicted as solid line. The resonance (order m = 1) is indicated by the arrow.

Near the center of the stop band, one narrow cavity resonance line at 3.9 µm is found. This is the first order resonance mode (m = 1) of the half-wavelength cavity. As shown by the solid line in Fig. 1, the whole experimental spectrum, in particular the stop band width and the cavity resonance position, is in very good agreement with simulations based on the transfer matrix method. In order to evaluate the finesse of the microcavity, the line width of the cavity mode has to be analyzed. For that, a high-resolution FTIR transmission spectrum of the resonance was recorded. The measured data is depicted as dots in Fig. 2. From a Lorentzian line fit, a line width $\delta\lambda$ of only 5.2 nm is deduced. This corresponds to a very high finesse of the microcavity structure of $F = \lambda/(m\ \delta\lambda) = 750$ for the m = 1 order mode. Using $F = (\pi R^{0.5})/(1 - R)$, this in turn corresponds to a mirror reflectivity R of 99.7%. Such a high reflectivity mirror with only few layer pairs is well suited for realization of laser devices.

The solid line in Fig. 2 represents the transfer matrix simulation which is in perfect agreement to the experiment when cavity losses corresponding to an extinction coefficient κ of 0.0028 are included. These losses are very low because they are on the order of magnitude of the residual absorption of PbEuTe *below* the band gap energy. They may arise from background absorption in the cavity material or from interface roughness between the layers in the multilayer cavity structure. These results demonstrate that our Bragg mirrors not only exhibit one of the largest refractive index contrasts and broadest stop bands, but also provide very high reflectivity values well above 99 % for only three Bragg layer pairs. To our knowledge, only one other such mirror with comparable index ratio and band width has been reported in the literature up to now. However, for this mirror consisting of BaF_2 and PbEuSe grown on (111) Si substrates, the measured reflectivity was only 95 % for three layer pairs [5].

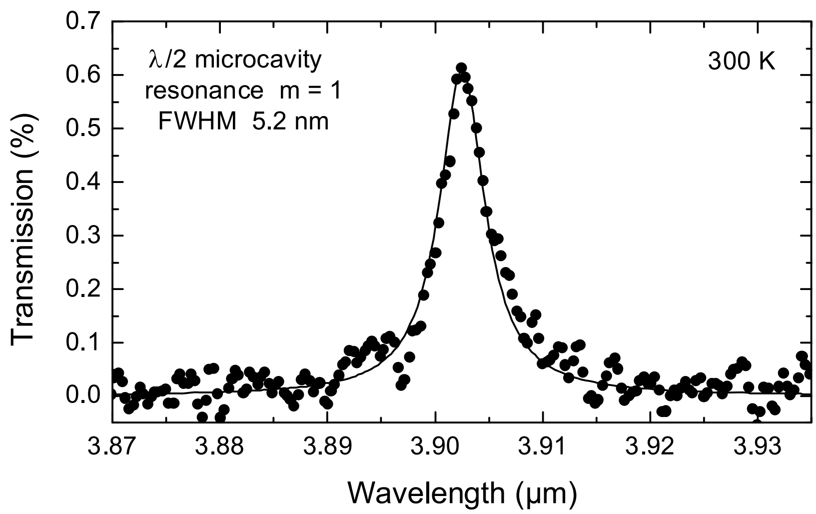

Fig. 2: High-resolution FTIR transmission spectrum around the cavity mode of the half-wavelength cavity at 300 K (dots). The corresponding transfer matrix simulation is shown as solid line.

Conclusion

To summarize, we have demonstrated MBE grown high-reflectivity broad band Bragg mirrors for mid-infrared device applications, using IV-VI semiconductors and BaF_2 as mirror materials. This material combination exhibits an exceedingly large difference in refractive index, with a corresponding index contrast ratio n_1/n_2 of up to 3.5. As a consequence, we have observed a very broad mirror stop band with a relative band width of 75% for $Pb_{0.92}Eu_{0.08}Te/BaF_2$ Bragg mirrors, in good agreement with our simulations based on the transfer matrix method. Both the index contrast and the stop band width are not only among the largest for MBE grown Bragg mirrors, but also for Bragg mirrors fabricated by other methods with less limitation on the material choice. As a decisive characteristic for the mirror quality, the finesse of cavity structures produced on basis of these Bragg mirrors has been shown to be 750 for a half-wavelength microcavity which exhibits a narrow resonance line width of only 5.2 nm. From that, a mirror reflectivity higher than 99.7% is obtained for only three layer pairs. This evidences the high quality and efficiency of MBE grown IV-VI/BaF_2 Bragg mirror structures, and underlines their high potential for practical device applications.

Acknowledgements

Financial support from the Austrian Science Fund FWF, Austria is gratefully acknowledged.

References

[1] W. Heiss, T. Schwarzl, J. Roither, G. Springholz, M. Aigle, H. Pascher, K. Biermann, and K. Reimann: “Epitaxial Bragg Mirrors for the Mid-infrared and their Applications”, Prog. Quantum Electron., Vol. 25, 2001, pp. 193 - 228.

[2] G. Springholz, T. Schwarzl, and W. Heiss: “Mid-infrared Vertical Cavity Surface Emitting Lasers based on the Lead Salt Compounds”, in Mid-infrared Semiconductor Optoelectronics, edited by A. Krier (Springer, London, 2006), pp. 265 – 301.

[3] J. L. Jewell, J. P. Harbison, A. Scherer, Y. H. Lee and L. T. Florez: “Vertical-cavity Surface-emitting Lasers: Design, Growth, Fabrication, Characterization”, IEEE J. Quantum Electron., Vol. 27, 1991, pp. 1332 - 1346.

[4] M. Tacke: “New Developments and Applications of Tunable IR Lead Salt Lasers”, Infrared Phys. Technol., Vol. 36, 1995, pp. 447 - 463.

[5] X. M. Fang, H. Z. Wu, Z. Shi, and P. J. McCann: “Molecular Beam Epitaxy of periodic BaF_2/PbEuSe Layers on Si(111)”, J. Vac. Sci. Technol., Vol. B 17, 1999, pp. 1297 - 1300.