Conclusions

The subject-matter of this work was the fabrication and characterization of macroporous silicon. Fabricated in a photo-assisted electrochemical etching process macroporous silicon is a flexible material system for the preparation of ordered porous structures within two or even three dimensions. That makes this material system interesting for applications in materials science. In combination with post treatment steps the shape of the material as well as the material itself can be altered. This was shown in the second chapter of the thesis in which the combination of macroporous silicon and atomic layer deposition was investigated. Due to the self-limiting chemical reactions in atomic layer deposition, the entire porous structure can be coated homogeneously. Furthermore, the replication into different materials was proposed and proven using the example of titanium dioxide. In result, this technique is a competitive method for fabricating ordered porous structures – especially three-dimensionally shaped ones – which are flexible in their geometry and in the utilized material.

The main focus of the work was the application of macroporous silicon as a photonic crystal. For applications in the field of telecommunication a device should work in a wavelength region of 1.5 µm. Based on earlier findings a 3D simple cubic arrangement of air spheres in silicon was taken as a reference design. As emphasized in chapter four the lattice constant of the structure has to be reduced to the sub-micrometer range to achieve the goal of operating at a wavelength of 1.5 µm. The material at hand had a doping density of $N_D = 8 \cdot 10^{16} \text{cm}^{-3}$ and a predefined lattice with a periodicity of 700 nm. It was shown that the controlled etching of straight pores as well as modulated pores is feasible with this material. However, for applications as a 3D photonic crystal the quality of the pore shape of the modulated samples has to be improved. In accordance with the experimental observations due to the variation of certain parameters two major factors could be isolated which have to be optimized for a better sample quality. On the one hand the importance of a uniform lithography was pointed out. On the other hand the electric conditions in the space charge region were studied and discussed in detail. The major conclusion that can be drawn from this part of the work is that especially the etching of 3D structures with a lattice constant below one micrometer is close to physical limits given by the required doping density of the material and the resulting breakdown conditions for small pore radii. From the presented calculations an optimized doping density of $N_D = 2 \cdot 10^{16} \text{cm}^{-3}$ could be derived for a material with a lattice constant of 700 nm. Although the breakdown voltage in this optimized material would still be low, a considerable decrease in the corrosion of the pore walls can be expected. Thus, it should be possible to realize 3D photonic crystals with improved optical capabilities compared to the presented measurement of a photonic stop band in the etching direction.

Beside the photonic band gap as an important property of a photonic crystal further effects
related to the dispersion relation can be expected. A detailed investigation of this topic was given in the last two chapters. Thereby, both aspects, theory and experiment, were considered and compared to each other. In the theory chapter the necessary background was introduced to calculate and analyze the complete dispersion relation of a photonic crystal. Especially for effects based on the refraction properties of a photonic crystal the entire reciprocal space has to be examined. For comparison with etched 3D macroporous silicon samples a model was proposed to describe the dielectric function of the crystals. The calculated dispersion relation of a 3D structure was analyzed and different effects were discussed. In particular, the negative refraction could be shown to be possible with the 3D macroporous silicon sample under consideration. The proposed process of characterizing the sample geometry and of calculating its dispersion relation is thereby of general meaning since it can be applied for different designs just by changing the description of the pore geometry.

In the frame of this work the theory was closely coupled to the experimental capabilities which enabled the possibility to directly compare theoretical and experimental results. Therefore, an experiment was designed which can be used to measure the beam shift induced by the refraction in the photonic crystal layer. It was found that the experimental characterization of the macroporous silicon sample is in excellent agreement with the theoretically predicted refraction behavior. Evidence was given for the fundamental phenomenon of negative refraction which is possible in the presented 3D structure and also for other effects related to the dispersion relation like beam shaping or prism-like spectral beam widening. Thereby, special attention should be given to the fact that all the achievements in this work rely on 3D photonic crystal structures operating in the infrared region of the electromagnetic spectrum.

Finally it can be concluded, that the material system macroporous silicon is a promising candidate for the future integration of photonic technologies and devices in silicon.