Tunable Fabry-Perot-filters based on InP/air-gap mirrors

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Tunable optical filters can cover spectral broad ranges in sensor technology and data communications either as a single element or as a group of elements arranged in an array. MOEMS Fabry-Perot filters make use of the physical and technological advantages resulting from miniaturisation. The cavity length is tuned by electrostatic actuation, leading to an optical tuning range of 221 nm in the near IR at 1.55 µm.

The Fabry-Perot set-up is widely used for optical devices such as interferometers and laser resonators, but is also a common design for narrowband optical filters with applications in sensor technology and data transmission. Multiplexer systems (e.g. DWDM), transmitting numerous signals in a single optical fibre, implement these filters to separate the channels at the detector. In spectroscopic applications the transmitted wavelength ("filter dip") can be adjusted to match characteristic parts in a spectrum. Filters that are tunable over a wide range have important advantages compared to the common static designs: a single filter can switch between different channels in a demultiplexer, or can be used for broader ranges in spectroscopic measurements. Due to the tunable filter wavelength these devices can be used flexibly for a broad range of tasks, as a wide and continuous spectral range can be covered by a small number of devices. Dynamic spectral adjustment is possible as well, for example when switching channels or to match shifting of a light source.

Optical data transmission and optical measurement methods make use of fibre optical systems. As glass fibres have lowest absorption at wavelengths around 1.55 µm, indium phosphide is used as the filter material. The direct compound semiconductor provides the best basis for the integration of active and passive optoelectronic components in this band, and is additionally useful throughout the 1–2 µm range relevant to sensor technology.

Applying MOEMS technology (micro optical electrical mechanical system) offers advantages for the fabrication of Fabry-Perot filters regarding high integration density, parallel processing of numerous devices and designs with a longitudinal single mode cavity. Most notably, the relative strength of physical forces in the micro- and nanometre range has to be considered – by introducing a scaling factor to the appropriate physical equations it appears that for small structures the influence of mechanical and magnetic forces decreases, whereas thermal expansion and electrostatic force dominate this domain [1]. This effect is not only utilised for the actuation principle, but also gives an explanation as to the low material fatigue and high mechanical stability of these miniaturised structures.

Design and properties

Figure 1 illustrates a tunable filter device. The circular filter membrane is suspended from four supporting posts, which double as electrical contacts. The cavity and surrounding mirrors can be seen in the cross-sectional schematic. As high reflectivity is necessary to obtain high finesse, the mirrors are implemented

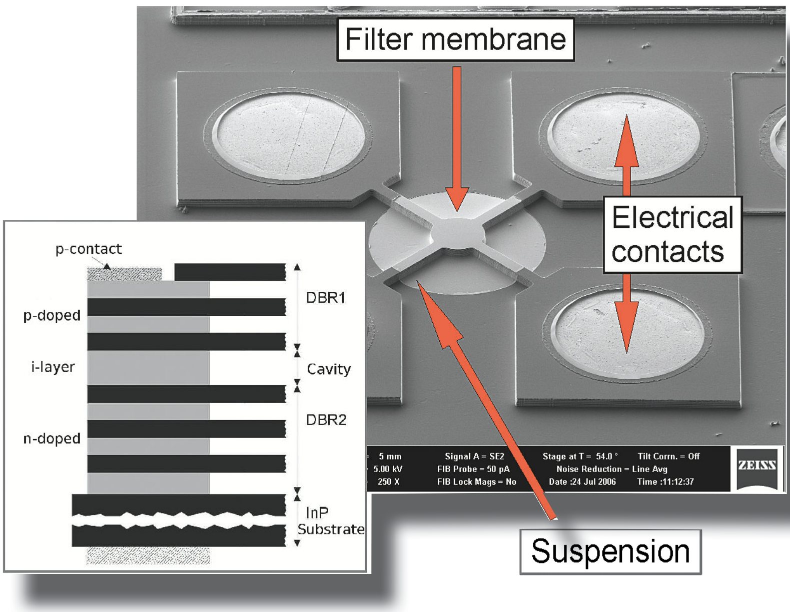

Figure 1: Photo of a filter device and its elements (right) and cross sectional schematic at the transition between supporting post and air-gap structure (left)

Originally published in German in Photonik 6/2007

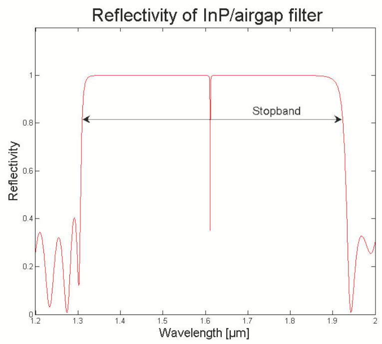

Figure 2: Numerical calculation of the spectral reflectivity of a Fabry-Perot filter with InP/air-gap DBR mirrors and λ-cavity. The transmitted filter dip can be widely tuned within the range of the stopband

as distributed bragg reflectors (DBR). These comprise alternating layers of InP membranes and air-gaps to maximise the refractive index contrast, and achieve over 99.5% reflectivity after only three InP membranes. The parameters of these bragg structures determine the stopband, which has to be much wider than the intended tuning range.
Due to the properties of DBRs, longitudinal single mode filters can be implemented for cavity lengths exceeding λ/2 as long as higher modes have a spectral position outside the stopband. This also allows control of the spectral linewidth of the filters (**figure 2**).
Tuning of the filter dip is performed by electrostatic actuation. The DBR mirrors are p-doped and n-doped, respectively, whereas the cavity layer is intrinsic, i.e. undoped. By applying a reverse bias between the mirrors the cavity length is reduced due to electrostatic attraction and hence the filter dip is shifted towards a shorter wavelength.

Fabrication of filter devices

The filter devices are fabricated by means of micro- and nanotechnology in a cleanroom environment. The process bases on four principal steps (**figure 3**), supplemented by additional procedures. Initially a multilayer system consisting of InP layers – the filter membranes – and GaInAs sacrificial layers is grown by epitaxy. The sacrificial layers are later removed to obtain the air-gaps. For the epitaxy a MOCVD (metal organic chemical vapor deposition) process is utilised, delivering crystaline layers in the nm range with very high interface quality. Doping of the mirrors and the layers for electrical contacts is also carried out. In the next process step the lateral design of the devices is defined. For this the structure of a photoresist mask is transferred to the InP/GaInAs multilayer system by reactive ion etching (RIE). As material is removed by physical ion bombardment, the process has only low selectivity and results in similar etch rates for both kinds of layers. The etching is anisotropic, i.e. only perpendicular to the substrate plane, and hence vertical profiles (mesa structure) occur. Subsequently, the GaInAs sacrificial layers have to be removed to obtain the air-gaps. For this purpose wet chemical etching (FeCl3) is employed to remove GaInAs with high selectivity over InP. In the final process step the etchant has to be removed from the gaps inside the filter. Since conventional drying methods lead to collapse of the thin membranes due to capillary forces, a so-called "critical point drying" process is used. By increasing pressure and temperature of a (liquid) CO_2 medium the critical point is reached where the interface between liquid and gaseous phase vanishes – on exceeding this point the CO_2 can then be removed safely. Additional procedures in the fabrication of Fabry-Perot filters include the deposition of electrical contacts or are process-related, as for example the generation of etch protection layers.
For released MEMS structures stress within the layers is a significant problem, leading in this case to bending and thus sticking of filter membranes and ultimately resulting in damaged devices. Although the compound semiconductors are deposited perfectly lattice matched, an undesirable arsenic carry-over effect between the GaInAs layers and the lower part of the InP membranes can not be avoided completely [2]. The resulting gradient stress leads to noticeable deformation of the structures. To adjust the local lattice mismatch in the InP layers, compensation layers are introduced during the epitaxy process. The properties of compensation can be investigated using cantilever test structures incorporated into the processed samples. The experimental results of different compensation layers are shown in **figure 4**, perfect compensation being achieved for a thickness of 43 nm [3].

Results and enhanced structures

The optical characterisation of various filters fabricated by the described process yielded wide tuning ranges. Filter devices with a very low actuation voltage of 3.2 V showed a tuning range of 142 nm [4], while filters designed for highest tuning

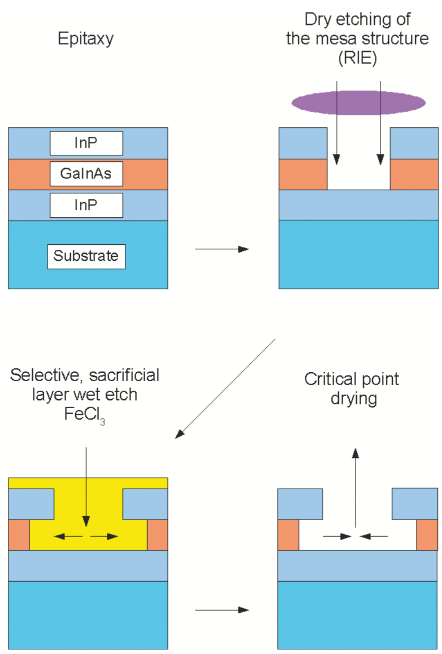

Figure 3: Basic four steps of the process for fabrication of the MOEMS filters – simplified model with only one sacrificial layer (orange)

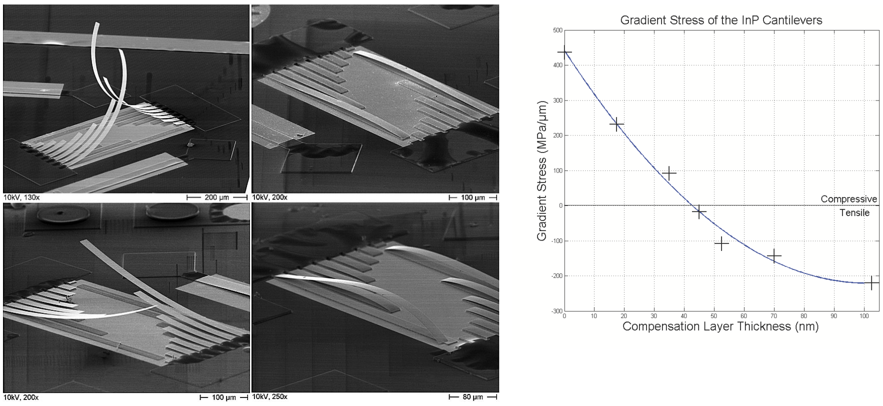

Figure 4: Compressively strained cantilevers bend up (left), the tensile ones bend down (right). By introduction of compensation layers with adjusted thickness deformation can be avoided completely. The data plot depicts the results of the experimental work

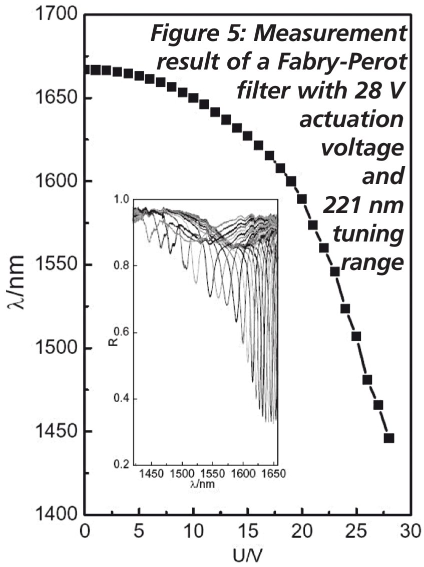

Figure 5: Measurement result of a Fabry-Perot filter with 28 V actuation voltage and 221 nm tuning range

range achieved 221 nm at 28 V (**figure 5**) [5]. The mechanical full tuning cycle time is in the order of 10 µs.

By integration of a photodetector, or by applying a diffractive-optical or photonic crystal structure on the membrane (**figure 6**), the filter properties can be expanded and improved. For example, polarisation control [6] or lateral mode confinement are potential applications. As Fabry-Perot filters are widely used as laser cavities as well, tunable VCSEL for the spectral rang >1.3 µm are a relevant topic in research [7,8].

Conclusion

The MOEMS Fabry-Perot filters presented in this article are tunable over a wide spectral range in the near infrared and have versatile applications in photonics and spectroscopy. The devices make use of the advantages of miniaturisation, including process related properties and integration density, and benefit in particular from a relative change in the physical forces at these scales. Use of compound semiconductors, such as InP, is important for optoelectronic devices due to their band structure, although processing is more complicated than for example for Si. Further research is intended on integrated active and passive devices and structures on filter membranes.

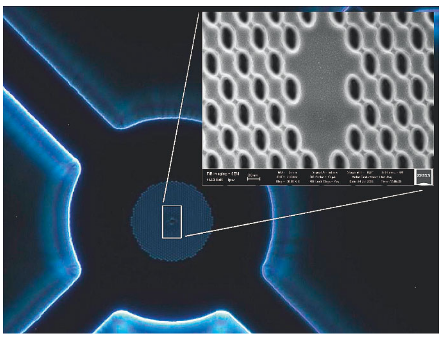

Figure 6: Additional photonic crystals or diffractive optical elements on the filter membrane add new properties, e.g. polarisation control

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Originally published in German in Photonik 6/2007