Elastomer based electrically tunable, optical microcavities

Irmgard Slowik1,4, Nils M. Kronenberg2, Markus Franke3,4, Axel Fischer1, Andreas Richter1,4, Malte C. Gather2 and Karl Leo1,4
1Institut für Angewandte Photophysik, Technische Universität Dresden, George-Bähr-Strasse 1, D-01069 Dresden, Germany
2SUPA, School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews KY16 9SS, Scotland, UK
3Institut für Halbleiter- und Mikrosystemtechnik, Polymere Mikrosysteme, Technische Universität Dresden, D-01062 Dresden, Germany
4Center for Advancing Electronics (cfaed), Technische Universität Dresden, D-01062 Dresden, Germany

Reconfigurable filters with small bandwidth were realized, and tunable elements are mostly realized by microelectromechanical systems (MEMS). For this purpose, optical sensing and simple processing. However, optical sensitivity and a reduced response time are promising high sensitivity and a reduced response time. Particularly for biological applications or chemical point-of-care analysis, as well as telecommunications.

Dielectric elastomers (DE) are promising materials for electromechanical applications because of their ability to deform reversibly under applied voltage up to very high strains. Recent applications include artificial muscles, loudspeakers, stretchable integrated circuits, and generators. Due to their high transparency and flexibility, they show great potential to realize tunable optical elements like tunable phase plates, gratings or microcavities. Fig. 1 shows the operation principle of a dielectric elastomer actuator. When an external voltage is applied, the elastomer film gets squeezed due to the electrostatic pressure. Pielmeier et al. demonstrated that in a plate capacitor set-up, the effective pressure is written as:

$$p = \varepsilon_0 \varepsilon_r E^2 = \frac{\varepsilon_0 \varepsilon_r V^2}{z^2}$$

(1)

where \(\varepsilon_0\) is the dielectric constant, \(\varepsilon_r\) the relative permittivity, \(E\) the electric field strength and \(z\) the thickness of the elastomer film. In the simplest form for an unloaded, unconstrained actuator, the thickness strain is calculated by Eq. (1) and the elastic modulus \(Y\), which is defined as ratio of stress \(\sigma\) to strain \(s\), so that \(\sigma = Y s\). For small strains up to 10%, it can be assumed that \(z = 3\), where \(z_0\) is the initial thickness of the elastomer film.

Hence, the thickness variation \(\Delta z\) is described for small strains by:

$$\Delta z = \frac{\varepsilon_0 \varepsilon_r V^2}{Y z_0}.$$  

(2)

As the dielectric elastomer used in this work is incompressible, flexible electrodes are essential for the realization of the actuator. Compliant metal electrodes on soft elastomers are rather difficult to achieve due to the large difference in the elastic modulus of the used elastomer (kPa range) and the metal (tens of GPa). Furthermore, rigid substrates influence the actuator performances due to the one-side-constraint of the soft-dielectric film. Particularly on thin elastomer films, a metal electrode is expected to have a significant stiffening impact on the structure. Also, the low elasticity of metals (2-3%) hampers the usage of metal electrodes as cracks are formed during stretching of the elastomer film. Improvements in the elasticity of metal films were achieved via structuring of the electrodes.
either in zig-zag, coil or as horseshoe shaped tracks. An alternative means to keep the stiffening impact of the metal electrode low but at the same time maintain a closed film with reasonable conductivity, is to reduce the lateral dimension of the metal layer.

Here, we report on metal-elastomer-DBR microcavities as schematically illustrated in Fig. 2 (a). The bottom mirror is formed by a distributed Bragg reflector (DBR) made of 21 alternating layers of SiO$_2$ and TiO$_2$, deposited on a glass substrate with $\approx 90$ nm of indium tin oxide (ITO) layer serving as the bottom electrode. A film of an ultra-soft poly(siloxane) based elastomer (stiffness $\approx 3$ kPa) produced by spin coating and heat curing is deposited on the DBR. By variation of the rotation speed, the thickness is adjusted between 3 and 15 $\mu$m. To increase the surface energy of the elastomer layer, a soft oxygen plasma treatment is performed prior to the physical vapor deposition. The top mirror and electrode are formed by a 25 nm thick silver layer, which is deposited on the elastomer layer by physical vapor deposition. The film thickness used here represents a film on the rigid substrate, the active deformation occurs mainly at the rim of the top metal electrode where the compressed material expands to the metal free area. The variation of the cavity layer thickness leads to a change of the mode spectrum of the microcavity (Fig. 3 (b)). A change in the cavity spectrum under applied voltage is observed by reflection measurements close to the metal edge (Fig. 3 (c)). The quadratic dependence between applied voltage and cavity deformation (compare Eq. 2) is confirmed by fitting a simple quadratic function (Fig. 3 (d)).

To investigate the spatial distribution of the actuation, cross sections at the metal edge are analysed. Fig. 4 (a) depicts the profile of the actuated sample discussed in Fig. 3. The compression of the cavity underneath the electrode and the expansion outside the electrode area are phenomenologically described with a bi-Gaussian function for each peak (red dashed line). From this, the width of the deformation is estimated to be approximately 50 $\mu$m. The performance of the actuator is further improved by structuring the top electrode, as depicted in Fig. 4 (b). In this case, narrow metal stripes (width, 90 $\mu$m) were realized by physical vapour deposition through a suitable shadow mask. The profile of the actuated device exhibits two maxima of deflection with around 35 $\mu$m width while material is squeezed out of the electrode area. Therefore the cross section shows a ‘W’-like shape.
FIG. 3. Optical characterization of the metal-elastomer-DBR cavity (25 nm Ag, 12 µm elastomer): (a) Confocal microscope image of metal electrode edge under monochromatic illumination at 650 nm for various applied voltages. A change of interference fringes at the rim of the metal film indicates a thickness change at these positions. (b) Simulated transmission spectra of the metal-elastomer-DBR cavity with transfer matrix algorithm shows the shift of mode spectrum depending on the optical thickness of the cavity layer measured in quarter wavelength (qw) for a design wavelength of 630 nm. (c) Reflection spectra measured for different applied voltages. (d) Change in position of a mode located around 633 nm and the decrease in cavity thickness derived from this shift as a function of the applied voltage (black dots). The blue dashed line represents a quadratic fit of the measured data using Eq. 2.

However, the quality factors measured close to the metal edge are much lower than in the reference shown in Fig. 2(b). This effect occurs because of the shadow mask evaporation not sharp but more trapezoid-like metal edges are formed. Higher quality factors with expense of the tuning range can be achieved with increasing distance to the edge. Hence, transmission spectra of the tunable cavity are measured taken with a distance of 50-100 µm to the metal edge for different applied voltages using a microscope setup (objectives: focusing 25x NA 0.5, imaging 50x NA 0.8) shown in Fig. 5. Due to the non-homogeneous deformation of the elastomer layer (see Fig. 4(a)) a smaller wavelength shift up to 1 nm is detected compared to the reflection spectra shown in Fig. 3(c). Even so, because of the large spot size (≈ 50 µm) a broadening of the modes occur for increasing external voltage. Therefore, the quality factor of the cavity drops from 700 to 300 at 90 V respectively. Nevertheless, the effect is less pronounced for smaller spot size or lower external voltages. Furthermore, the quality factor can be enhanced using thicker metal layers e.g. increasing the thickness of the silver layer to 50 nm would roughly double the quality factor of the optical cavity. However, a thicker metal electrode leads to an higher stiffening impact on the soft elastomer and therefore will cause a lower tuning range of the cavity. On the other hand, the tunability can be increased using thin-
FIG. 5. Transmission spectra for the metal-elastomer-DBR cavity shown in Fig. 4 (a) measured in a microscope setup with a spot size of about 50 µm (objectives: focusing 25x NA 0.5, imaging 50x NA 0.8). The spectra are taken with a distance of 50-100 µm to the edge. Under applied voltage the position of the optical modes is shifted up to 1 nm to lower wavelength because of the compression of the soft elastomer cavity layer. Due to inhomogeneous deformation of the elastomer layer, the quality factor decreases from 700 (0 V) to 300 (90 V).

FIG. 6. (a) Averaged capacitance change ∆C under applied voltage V measured by impedance spectroscopy (f = 100 kHz, Vrms = 200 mV) for 10 cycles. Following Eq. ?? the inverse capacitance follows a quadratic dependence on the applied voltage (blue dashed line). The inset shows the capacitance for 5 sweeps from -40 to 40 V. (b) Schematic view of the measured sample structure; (c) Sample is described as a parallel RC element, while the capacitance of the DBR can be neglected.

In conclusion, we have demonstrated an electrically tunable, optical filter realized by a tunable metal-elastomer-DBR multi-half wavelength microcavity employing a thin film dielectric soft elastomer actuator. Applying a voltage between a bottom transparent electrode on the glass substrate and the top metal layer results in a deformation of the soft elastomer. We observed a reversible mode shift of the cavity modes up to 14 nm related to a cavity thickness change of about 200 nm. The electrostriction follows a quadratic voltage behaviour, allowing a control of the resonant wavelength in a range below 1 nm. Larger actuation can be achieved by using elastomers with lower Young’s modulus as cavity layer or altering the metal layer thickness. Furthermore, the performance can be improved using structured electrodes reducing the stiffening impact of the metal electrode on the soft elastomer layer. Since the devices are fabricated with low cost processing like physical vapor deposition and spin coating, the results offer the possibility to realize cost efficient and simple processable tunable optical elements, e.g. filters, resonators, or display application.

Acknowledgement: This work is supported in part by the German Research Foundation (DFG) within the Cluster of Excellence Center for Advancing Electronics Dresden (cfaed) and by the European Social Fund via the OrganoMechanics project. M.C.G. and N.M.K acknowledge support by the Scottish Funding Council (via SUPA) and the Human Frontier Science Program (RG0074/2013).


21X. Zhao, and Q. Wang, “Harnessing large deformation and insta-