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Silicon-based near-infrared tunable filters filled with positive or negative dielectric anisotropic liquid crystals

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Complementary metal-oxide-semiconductor-compatible tunable Fabry–Pérot microcavities filled with liquid crystals (LCs) were realized and studied in the near-infrared region. The microcavities were produced by chip bonding technique, which allows one to infill LC between two $[SiO_2/Si]_3\lambda/4\,(\lambda=1.5\,\mu m)$ dielectric Bragg reflectors separated by 950-nm-thick SiO_2 posts. Liquid crystals with positive and negative dielectric anisotropy were used, i.e. MerckE7 ($\Delta\epsilon=13.8$) and Merck-6608 LC ($\Delta\epsilon=-4.2$). Mirror-integrated electrodes allow an external bias to induce an electric field and to tune the LC properties and, hence, the microcavity resonance. Electric-field-induced shifts of the second-order cavity modes of 127 and 49 nm were obtained for Merck-E7 and Merck-6608 LC, with driving potentials of 5 and 10 V, respectively. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1630692]

Integration of miniaturized electro-optical devices, such as modulators, shutters and switches in silicon based optical circuits is necessary to achieve all silicon based photonics.[1] Silicon has a very low electro-optical coefficient, which implies large fields to achieve light modulation. To overcome this fundamental limitation, one proposed approach is the hybrid integration on Si of materials with large electro-optical coefficients, such as liquid crystals (LC).[2] Some efforts were made to use LCs for switching at 1.55 μm, by filling a Fabry–Pérot-type cavity with LCs.[3–5] Recently other alternative structures such as porous Si or two-dimensional photonic band gap crystals have been investigated.[6–8]

The aim of the present work is to develop a process sequence able to realize a LC in-filled Fabry–Pérot microcavity (MC) on a Si substrate. With respect to other structures[3,4]—explored in the past—our approach differs for (i) a spacer distance reduced down to 1 μm, (ii) a planar electrode geometry, and (iii) a process sequence able to exploit as much as possible to standard complementary metal-oxide-semiconductor (CMOS) processing. Moreover, we used two different nematic LCs having positive (Merck-E7 LC) and negative (Merck-6608 LC) dielectric anisotropy and addressed some problems regarding the alignment of LC within a silicon-based microcavity.

To keep our approach compatible with standard CMOS technology, we have used the standard Si processing fabrication tools to obtain the mirrors for the cavity and then, as postprocessing steps, the assembling of the cavity and LC infilling was done. More in detail, a sequence of oxidation and poly-Si deposition, through an in-line low-pressure chemical-vapor-deposition machine, was used to obtain three period distributed Bragg reflectors (DBRs),[9] i.e., mirrors for the Fabry–Pérot microcavity. DBRs were realized on 4 in. wafers, either quartz or ⟨111⟩ high resistivity (5 kΩ cm) Si. In order to have the DBRs centered at 1.55 μm, the SiO_2 and the Si layers' thickness of the DBRs were 260±20 and 110±10 nm, respectively. The last poly-Si deposited layer was a phosphorous doped poly-Si with a resistivity of $5\times10^{-3}\,\Omega$ cm to utilize this layer also as an electrode: in this way the electrodes are integrated within the mirrors. On one mirror a 950±20-nm-thick SiO_2 layer (later named spacer) was deposited. The SiO_2 layer was further defined by means of a lithographic step and wet etching process to realize the SiO_2 spacer, which defines the mirror distance and the area of the device later on occupied by the LCs. Afterwards, the wafers were diced in the form of 2 cm×2 cm or 1 cm×3 cm chips to obtain the bottom and the top mirrors, respectively, of the MC. All the electrode-mirror surfaces were carefully cleaned and, when parallel homogeneous alignment was wanted, rubbed with lens paper. Then, the mirrors were bonded face to face using two-component epoxy glue and keeping the pieces under slight pressure to assure that the 950-nm-long SiO_2 spacer defines the distance between the mirrors. To achieve homeotropic alignment the assembled cavity was treated with a solution of lecithin dissolved in chloroform creating a monolayer of lecithin. Finally, the MCs were filled with the LC keeping the cell temperature higher than the clearing temperature T_c (58 °C for Merck-E7 LC, 90 °C for Merck-6608 LC) of the LC, then slowly cooled down to room temperature. The uniform planar alignment (for Merck-E7 LC) and the vertical alignment (for Merck-6608 LC) of the LC in the cells were checked by a microscope using polarized visible light and by mid-infrared

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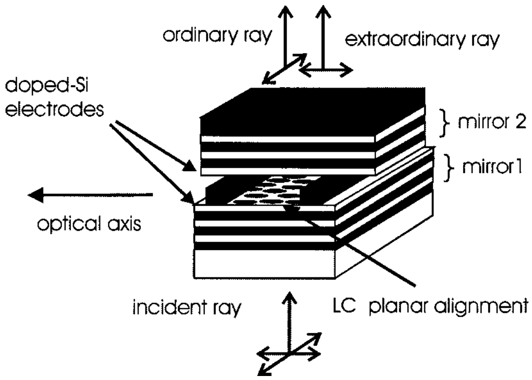

FIG. 1. Scheme of the Fabry–Pérot microcavity filled with positive dielectric anisotropy LC in the off-state (planar alignment).

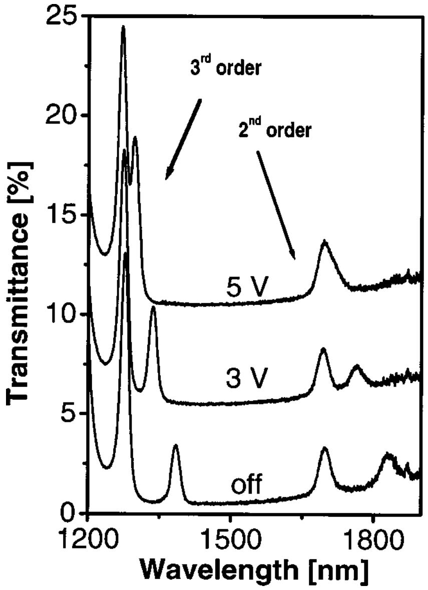

FIG. 2. Room temperature transmission spectra of the Fabry–Pérot microcavity filled with Merck-E7 LC (positive dielectric anisotropy) as a function of the applied potential. Spectra measured at 3 and 5 V are shifted for clarity.

spectroscopy with polarized IR light. Figure 1 shows a schematic of the MC, showing as an example the uniform planar alignment of the Merck-E7 LC in the off state $(V=0)$.

Application of a potential between the poly-Si electrodes has opposite effects on the two types of LCs. For positive dielectric anisotropic LCs, the director is reoriented towards the electric field direction, whereas for negative dielectric anisotropic LCs the director is reoriented perpendicular to the electric field direction.[2] We used an ac (1 kHz) bias to avoid electrochemical decomposition of the sample.

For Merck-E7 LC (positive dielectric anisotropy), the application of an external potential orientates the director, e.g., the optical axis, from the rubbing direction towards the electric field direction. As a consequence, the projection of the extraordinary refractive index n_e along the light propagation direction changes. The angular dependence of $n_e(\theta)$ is given by[4]

$$n_e(\theta)=\left[\frac{\sin^2(\theta)}{n_e^2}+\frac{\cos^2(\theta)}{n_o^2}\right]^{-1/2}, \tag{1}$$

where n_o is the ordinary refractive index, and θ the angle between the optical axis and the light propagation direction.

Figure 2 shows the transmission spectra of a MC filled with the Merck-E7 LC in the near-infrared region for various voltages. All spectra were recorded with a Cary 5000 spectrometer. Cavity modes are observed at about 1800 and 1300 nm, due to the second and third order cavity resonances. As expected, each mode is split in two transmission resonances: one is strongly field dependent and caused by the extraordinary wave, whereas the second one remains essentially unchanged and is due to the ordinary ray.[4] The overall shift for the extraordinary peak is larger for the second order resonance than for the third order resonance. Considering the peak positions of the second order cavity modes in the off state we obtain an approximate value of the mirror distance $d\approx\lambda/n$. The cavity modes are at 1695 and 1832 nm for the ordinary $(n_o=1.521)$ wave and for the extraordinary wave $(n_e=1.746)$, which results in $d=1040$ or 1049 nm. These values are in good agreement with the nominal spacer distance of 950 nm. In Fig. 3 the position of the second order cavity mode of the extraordinary wave (λ_e) is reported as a function of the applied potential. The threshold voltage is about 1.5 V. Below threshold no wavelength shift is observed due to the Fréedericksz effect.[10] An applied potential of 5 V resulted in an overall peak shift of 107 nm.

For Merck-6608 LC (negative dielectric anisotropy) application of an external electric field induces a reorientation of the director from the vertical alignment towards the horizontal alignment, consequently the extraordinary refractive index changes. Since there is no preferential orientation of the director within the horizontal plane, numerous domains are formed, which results in a depolarization of the ordinary and extraordinary ray.

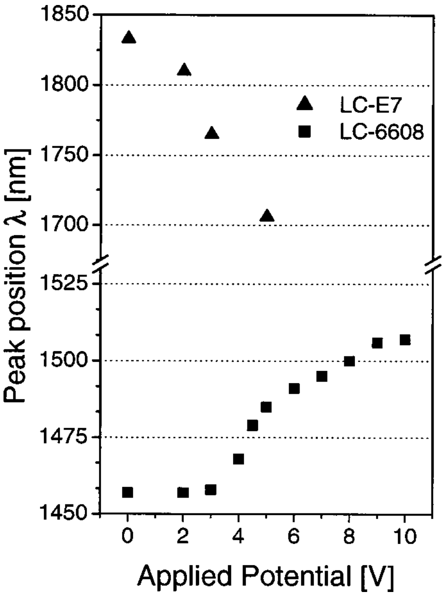

FIG. 3. Peak position λ of the second order mode as a function of the applied potential (ac, 1 kHz) of MCs filled with the liquid crystals Merck-E7 LC and Merck-6608 LC.

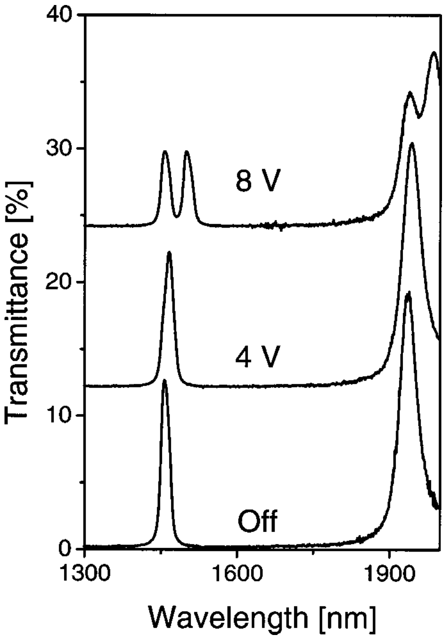

FIG. 4. Room temperature transmission spectra of the Fabry–Pérot microcavity filled with Merck-6608 LC (negative dielectric anisotropy) as a function of the applied potential. Spectra measured at 4 and 8 V are shifted for clarity.

Figure 4 shows the transmission spectra for the MC filled with Merck-6608 LC. For no bias, the ordinary and the extraordinary rays coincide and a single resonance is seen for the various cavity modes. When a bias is applied, the LC reorientate and a splitting in the resonances is observed. From the zero-bias resonance, an estimate of $d = 987\,\mathrm{nm}$ with $n_o = 1.476$ is obtained.[11] The bias induced second order resonance shift for the extraordinary wave (λ_e) is reported in Fig. 3. A bias of 10 V causes a peak shift of 49 nm. The threshold voltage for Merck-6608 LC is approximately 3 V. The quality factors $Q = \lambda/\Delta\lambda$ for both microcavities are in the range from 80 to 90, slightly depending on the actual microcavity investigated.

In conclusion, a prototype device based on the in-fill of a microcavity produced with standard CMOS facilities has been presented. This is a proof of principle and more work is needed to optimize the cavity structure in order to narrow the microcavity resonance and increase the transmittance of the resonancies in order to decrease the insertion losses into the optical switch. It is clear that the microcavity resonance could be tuned to cover the *S*, *C*, and *L* optical bands of the third telecommunication window by simply varying the thickness of the SiO_2 spacer between the two DBRs. Of the two LCs tested, Merck-6608 LC with negative dielectric anisotropy is more promising for applications because of the ease of its orientation on the cavity surface based on the availability of the orienting layers such as lecithin.

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