**SCIENCE CHINA**
**Information Sciences**

• LETTER •

February 2025, Vol. 68, Iss. 2, 129403:1–129403:2
https://doi.org/10.1007/s11432-024-4249-2

# Electro-optic tuning in ferroelectric capacitor with photonic crystal nanobeam cavity

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Received 24 September 2024/Revised 14 November 2024/Accepted 27 November 2024/Published online 15 January 2025

**Citation** Wang T T, Zhang Y, Yao D Y, et al. Electro-optic tuning in ferroelectric capacitor with photonic crystal nanobeam cavity. Sci China Inf Sci, 2025, 68(2): 129403, https://doi.org/10.1007/s11432-024-4249-2

Silicon photonics has provided a platform for the convergency of photonic devices and electronic circuits, facilitating the development of optical telecommunications and optical interconnects on chip [1]. As the basic building block of optical communication systems, electro-optic tuning is expected to be more compact, high bandwidth, energy efficient, and allow for CMOS-compatible fabrication in the future [2]. Resonator-based electro-optic tuning has attracted more and more interest due to the small footprint, enhanced light-matter interactions and high energy efficiency. Compared with microring and microdisk resonators, photonic crystal nanobeam cavities (PCNBCs) realize higher quality factors, stronger light-matter interactions, ultrasmall mode volume and a much larger free spectral range (FSR) [3].

In this study, we propose an electric-optic tuning based on a ferroelectric capacitor and ultracompact PCNBC. The ferroelectric capacitor consists of an Au/P(VDF-TrFE)/Si stacked nanostructure. The silicon waveguide in PCNBC also serves as the bottom electrode. Owing to the hysteresis property of ferroelectric materials and the plasma dispersion effect of silicon, it is observed that the new electro-optic tuning phenomenon with hysteresis property is different from traditional electro-optic modulators. The device realizes a small footprint of 12 $\mu m^2$ and an energy consumption of 7.02 pJ.

Figure 1(a) shows that the ferroelectric capacitor is designed on a p-type SOI platform (a 220 nm-thick Si layer on top of a 2 μm-thick $SiO_2$ layer). Detailed parameters of PCNBC and device fabrication are illustrated in Appendix A. The metal-ferroelectric-semiconductor (MFS) stack nanostructure is formed, as seen in the optical image in Figure 1(b). The enlarged region of the device shows the scanning electron microscope (SEM) image of PCNBC.

The simulated electric field distribution profile of the cavity's first mode in $XY$ plane is calculated by the 3D finite element method (FEM), as shown in Figure 1(c). With the cavity mode evidently concentrating in the central area of PCNBC, an ultracompact effective mode volume of 0.054 $\mu m^3$ is confirmed, which is only 1.43% of lambda-cubic ($0.0143\lambda^3$) volume. Strengthened interaction between light and matter and ultrasmall footprint are guaranteed by detailed design in Appendix A.

At the wavelength of the communication band, according to the Kramers-Kronig dispersion relations, the complex refractive index change of silicon is induced by accumulated electrons and holes [4]. To explore the electro-optic tuning effect of the device, we measure the transmission spectra of the device as a function of the signal voltage (Vs) applied to the Au electrode. The voltage is swept linearly from −20 to 20 V and then back to −20 V. The platform and equipment are introduced in Appendix B.

As shown in Figure 1(d), the forward sweep (FS) begins at Vs = −20 V. The holes in silicon are attracted to the silicon surface. Accumulation of free carriers leads to the blue-shift of resonant wavelength and strengthened light absorption. When Vs > 0 V, a large proportion of holes are moved away from the interface, thus resulting in a redshift of the resonant wavelength. The ferroelectric polarization keeps pointing towards the top electrode until Vs reaches near 10 V (coercive voltage of ferroelectrics). Thus, when 0 < Vs < 10 V, the direction of the applied voltage is opposite to the direction of ferroelectric polarization. When the polarization reverses, the peak current of the ferroelectric capacitor causes an abrupt increase of free carrier concentration and therefore causes a sudden blue shift of the resonant wavelength. It is preliminarily verified by the measured $I$-$V$ curve in Figure 1(e). The resonant wavelength remains red-shifted with increasing voltage after the polarization is reversed. Similar process takes place during the backward sweep (BS).

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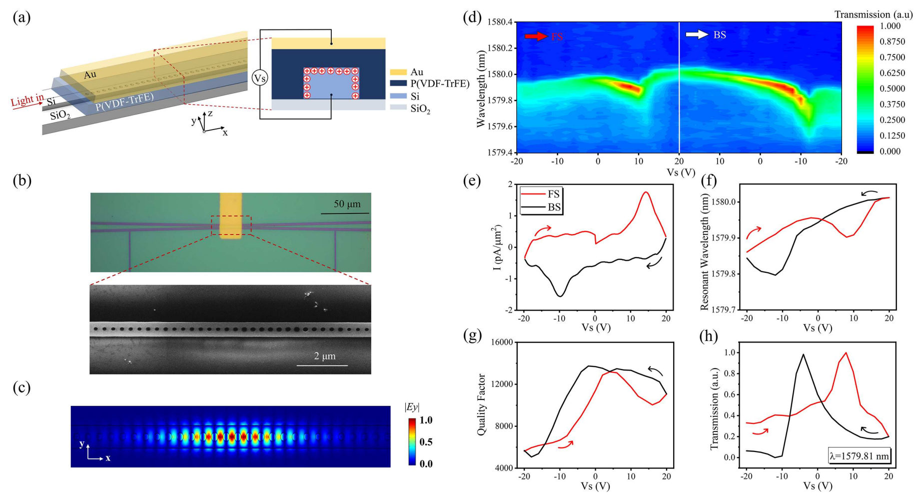


**Figure 1** (Color online) (a) Schematic illustration of proposed MFS structure capacitor and cross-section of the Au/P(VDF-TrFE)/Si stack. (b) Optical image of the actual device and scanning electron micrograph of the nanobeam cavity. (c) The simulation of PCNBC's first mode by FEM, demonstrating $|Ey|$ field distribution profile. (d) Measured transmission spectrums under different applied voltages. Vs is linearly swept from $-20$ to $+20$ V (FS), and then back to $-20$ V (BS). (e) Measured current of the ferroelectric capacitor as a function of Vs. (f) Extracted resonant wavelength shift during the voltage sweep in (d). (g) Calculated quality factor during the voltage sweep in (d). (h) Measured transmission as a function of Vs with input light fixed at 1579.81 nm.

As shown in Figure 1(f), the abrupt change of resonant wavelength coincides with the voltage where the current spike is caused by the ferroelectric polarization reversal, which confirms the effect of the current on the resonant wavelength. In addition to the resonant wavelength reflecting the refractive index change of the PCNBC, another optical property, light absorption, is represented by the quality factor ($Q$) calculated from the full width at half maxima (FWHM). Strengthened light absorption results in a drop of transmission and an increase of FWHM. Therefore, a lower $Q$ is obtained with higher absorption loss. Figure 1(g) shows that the $Q$ values of FS are lower than that of BS. This is related to the difference in ferroelectric polarization between two scanning processes. The ferroelectric polarization of FS strengthens the accumulation of holes on the p-type silicon surface, leading to an increase in light absorption. Whereas, ferroelectric polarization of BS weakens the hole accumulation and lessens the light absorption, leading to a higher $Q$.

Subsequently, the transmission of the fixed input light wavelength (1579.81 nm) was measured as a function of voltage, as shown in Figure 1(h). The peak transmission is observed at the voltage where the ferroelectric polarization is reversed. The difference between forward and backward scanning is due to the introduction of ferroelectric elements, which endows the device with promising prospects in electro-optic memory applications. $\pm 20$ V are used as write voltage storage signals and $\pm 10$ V are used as read voltages. The stored information is output as an optical signal. The conversion from electrical to optical signals is realized in the process of writing and reading information.

The ultralow energy consumption of the MFS structure capacitor is calculated by the following equation:

$$W = \frac{\mathrm{Pr} \cdot S \cdot \mathrm{Vs}}{2},$$

where $S$ is the device area, Pr is the remanent polarization after removing the applied voltage Vs. Value of Pr is obtained from the measured $P$-$V$ loop in Figure S4. The energy consumption of the fabricated device is estimated to be 7.02 pJ.

*Conclusion.* In conclusion, an ultracompact, energy efficient PCNBC based electric-optic tuning with an Au/P(VDF-TrFE)/Si ferroelectric capacitor is proposed and realized. The device demonstrates supreme properties such as a small footprint and low energy consumption. The ferroelectric poling of P(VDF-TrFE) is confirmed by measured $P$-$V$ hysteresis loop, while the ferroelectric based electrostatic doping effect is reflected in our on-chip electro-optic measurements. By introducing the hysteresis properties and memory applications of ferroelectrics to silicon photonic platforms, it opens a new path for the development of on-chip optoelectronic integration.

**Acknowledgements** This work was supported by National Key R&D Program of China (Grant No. 2023YFB4402303), Fundamental Research Funds for the Central Universities (Grant No. YJSJ24020), National Natural Science Foundation of China (Grant Nos. 62090033, 62025402, 62274128, 92264202, 62293522, 92364204), Zhejiang Provincial Natural Science Foundation of China (Grant No. LDT23F04023F04), and Innovation Fund of Xidian University.

**Supporting information** Appendixes A–E. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

**References**

1 Lockwood D J, Pavesi L. Silicon Photonics II. Berlin: Springer, 2011. 1–2
2 Li E, Gao Q, Liverman S, et al. One-volt silicon photonic crystal nanocavity modulator with indium oxide gate. Opt Lett, 2018, 43: 4429–4432
3 Siahkal-Mahalle B H, Abedi K. Ultra-compact low loss electro-optical nanobeam cavity modulator embedded photonic crystal. Opt Quant Electron, 2019, 51: 128
4 Reed G T, Mashanovich G, Gardes F Y, et al. Silicon optical modulators. Nat Photon, 2010, 4: 518–526