Silicon depletion-type microdisk electro-optic modulators using selectively integrated Schottky diodes

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Abstract: We report a design and analysis of silicon depletion-type microdisk electro-optic modulator with selectively integrated Schottky diodes. Our analysis suggests that the bandwidth is limited by the cavity lifetime rather than by the electrical performance.

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Silicon electro-optic (EO) modulators [1,2] using free-carrier plasma effect have been attracting considerable interest. In order to attain compact active devices, micro-scale resonators which are highly sensitive to refractive index changes are used. Most recently, Xu et al. [1] has reported > 5 GHz bandwidth using a microring resonator with integrated lateral injection-type p-i-n diode. However, such injection-type modulators have a shortcoming given by the carrier diffusion/recombination processes that can ultimately limit the intrinsic modulator bandwidth. Alternatively, depletion-type EO modulators are another approach for high-speed silicon-based optical modulators. Luxtera Inc. [3] has reported a 10 Gb/s modulation using a depletion-type silicon microring modulator with a lateral p-n device. Besides optimizing the device's electrical performance, the fundamental bandwidth limit due to the cavity photon lifetime should also be considered in designing microresonator-based optical modulators.

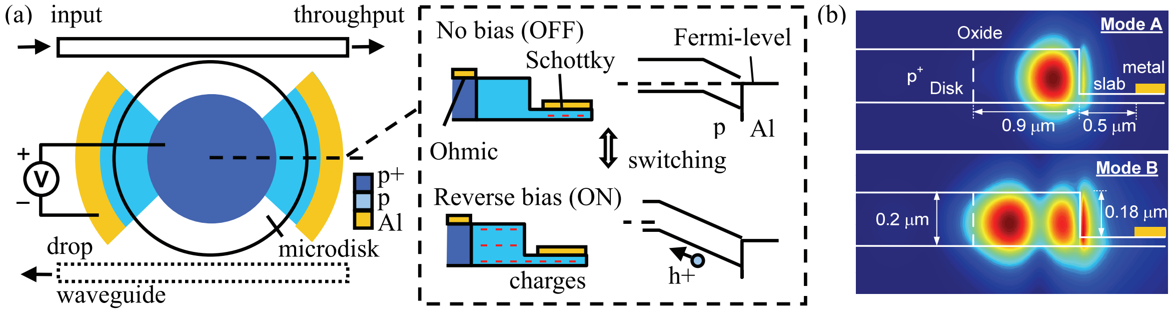

Fig. 1. (a) Schematic of a depletion-type microdisk modulator with selectively integrated Schottky diode. Al: aluminum. Inset shows the cross-sections and the band diagrams of the Schottky junction with the diode in "ON" and "OFF" states. (b) FDTD-simulated cross-sectional TE-polarized mode-field profiles of modes A (high-Q, 1^{st}-order) and B (low-Q, high-order). 3D-FDTD simulations assume a side-coupled waveguide width of 0.35 μm, a coupling gap of 0.2 μm, and a microdisk diameter of 5 μm.

In this summary, we propose a silicon depletion-type microdisk modulator using selectively integrated Schottky diodes along the microdisk rim. Fig. 1(a) shows the schematic of our proposed design. The Schottky contact which has the merit of less parasitic resistance can be made by depositing a metal film on the silicon surface as defining the contact patterns, and thus has the advantage in fabricating high-density-integrated photonic circuits as fewer processing steps is required. The microdisk rim is p-typed slightly doped in order to provide enough carriers for depletion, and the microdisk centre region is highly p-doped for ohmic contact.

The inset shows the cross sections and the band diagrams of the Schottky junction with the diode in "ON" and "OFF" states. When the diode is turned "ON," the depletion region extends into the microdisk rim and the majority hole-carriers are swept out by the internal electric-field. When the diode is "OFF," the external potential disappears and the dopant fixed charges at the depletion region sweep the majority carriers back. Hence, the majority carriers in the silicon microdisk rim are quickly swept in and out, rather than by slow diffusion/recombination which causes carriers leakage outside the active device region [2]. This also enables the design of selectively integrated diodes (only along portions of the rim) which potentially provides more functionality, such as high-speed optical switching with the addition of a side-coupled waveguide for channel dropping (Fig. 1(a)) while retaining the speed.

Depletion-type modulators offer further advantages in terms of the diode capacitance is low and reverse current is small, meaning low-power consumption. However, a possible shortcoming of the depletion-type device is the relatively narrow depletion width. That is partly the reason why the Schottky contact is selectively placed just outside the microdisk rim than near the microdisk centre. In order to have the depletion width extends into the microdisk rim, the rim doping concentration (and thereby the refractive index change) is limited, and thus imposes a high-Q resonance mode. The highly p-doped region coverage inside the microdisk should be small enough without affecting the resonance mode, yet wide enough in order to reduce the parasitic capacitance. Fig. 1(b) shows the cross-sectional mode-field profiles of mode A (high-Q, low-radial-order mode) and a higher-order mode B, calculated using a three-dimensional FDTD simulation tool. The highly-doped region is chosen to be only 0.9 µm from the microdisk rim without spatial overlap with mode A but a slight overlap with mode B [2].

We use a two-dimensional numerical simulation tool MEDICI in order to calculate the carrier concentration variation in the microresonator lightly-doped region. The refractive index change is calculated using free-carrier dispersion formulas according to Soref and Bennett. Fig. 2 shows the calculated plasma-induced refractive index variation from (a) 0 V to -8 V, and (b) -8 V to 0 V of a microdisk (Fig. 1(b)) and a comparable microring (see Fig. 2(b) inset). Both the rise and fall times (~5 ps) of the microdisk are faster than those of the microring. We attribute the faster switching time to a possibly more uniform electric-field distribution in the microdisk rim than in the small-cross-section rib waveguide structure (Fig. 2(b) inset). We obtain refractive index variation on the order of 10^{-4} by applying an 8 V reverse bias.

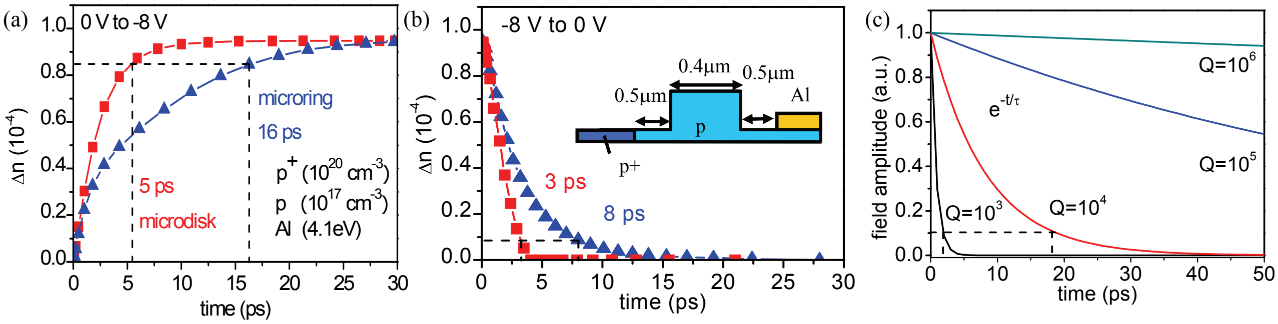

Fig. 2 The refractive index variation from (a) 0 V to -8 V, and (b) -8 V to 0 V of the microdisk (red) and the microring (blue). Inset: Schematic cross-section of the waveguide forming the microring resonator. (b) Illustration of the cavity resonance field decay $e^{-t/\tau}$ of different Qs.

With the increased speed in the integrated electrical device, we should also consider the fundamental bandwidth limitation of the compact microresonator modulator. It has been recognized that the bandwidth of a microresonator-based modulator is limited by the photon cavity lifetime [4]. In essence, resonance Q signifies the photon cavity lifetime τ ($Q = \omega\tau$, ω is the resonance frequency). Fig. 2(c) illustrates the resonance field amplitude decay (assuming $e^{-t/\tau}$) with different Qs. High-Q modes have relatively small modulation efficiency, yet the relatively long photon lifetime can limit the bandwidth. A refractive index variation of $\sim 10^{-4}$ can be used to shift a resonance mode with Q ~ 10^4, however, fig. 2(c) suggests that a Q ~ 10^4 mode has a decay time ~ 20 ps (> 5 ps of the electrical rise/fall times in the microdisk design). Thus, our modulator speed is fundamental limited by the photon lifetime although the design supports with an improved electrical speed. Our further work will focus on the on-going fabrication and experimental demonstration of the proposed Schottky diode depletion-type microresonator modulator.

References

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