# Ultralow-capacitance opto-electronic devices for femtojoule/bit photonics

**Kengo NOZAKI[1,2*], Shinji MATSUO[1,3], Takuro FUJII[1,3], Koji TAKEDA[1,3], Eiichi KURAMOCHI[1,2], Akihiko SHINYA[1,2], and Masaya NOTOMI[1,2]**

[1]Nanophotonics Center, [2]NTT Basic Research Laboratories, [3]NTT Device Technology Laboratories, NTT Corporation, 3-1, Morinosato Wakamiya Atsugi, Kanagawa 243-0198, Japan

*nozaki.kengo@lab.ntt.co.jp

Future microprocessors will need an unprecedented many-core architecture providing chip-scale optical communication, and for on-chip-com networks in particular, this architecture should be fully integrated with transmitters, photoreceivers, and other functional nanophotonic devices with low energy consumption. One of the challenges with these opto-electronic devices is to realize a device capacitance ($C$) as small as the fF level or less. Such devices are able to operate in the femtojoule/bit energy regime, which is required for future chip-scale photonic technology [1].

For a photodetector (PD), a low $C$ would allow connection to a high impedance load while retaining the RC bandwidth, and this would eliminate the need for power-consuming electrical amplifiers. Such a device is called a receiver-less PD and it provides ultralow-energy operation [2, 3]. Photonic crystals (PhCs) are promising as such small PDs because of their strong light confinement in an ultrasmall dimension. In this work, we use PhC-PDs with an embedded InGaAs absorption layer in an InP-based PhC waveguide, which we obtained using a compact buried-heterostructure (BH) (Fig. 1a and 1b). This structure can confine both photons and carriers in an ultrasmall space, and hence the length was reduced to just 1.7 μm and the capacitance was less than 1 fF (Fig. 1c). Even with such a small size, the optical responsivity remains high at 1 A/W and there is clear eye opening for a 40-Gbit/s signal (Fig. 1d). These features meet the demand for an amplifier-free PD terminated with a high impedance load. We investigate the integration of the PD with a several-kΩ load resistor to demonstrate on-chip light-to-voltage conversion. A conversion efficiency as high as 4 kV/W was observed, and the expected bandwidth exceeds 10 GHz. This suggests that the optical energy required for generating a CMOS voltage level (assumed to be 0.2 V) is less than 1 fJ/bit, which can be obtained without electrical amplifiers [3]. These results reveal a successful way of realizing an ultrasmall/ultralow-energy photoreceiver.

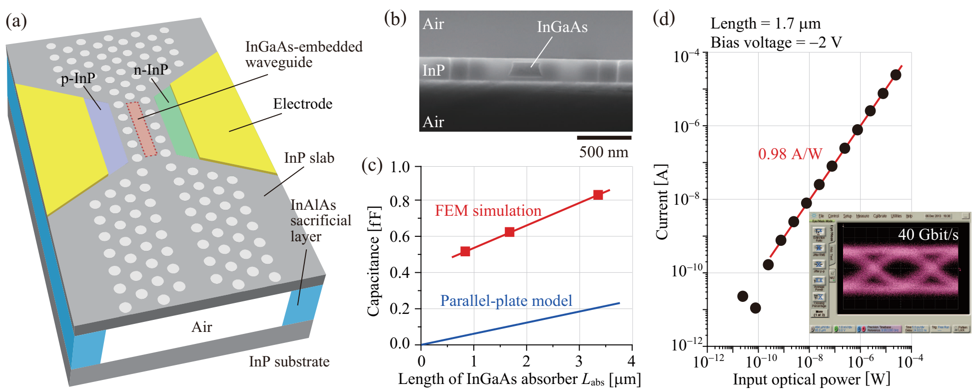


**Fig. 1 PhC-PD. (a) Schematic of PD structure. (b) Cross-sectional view SEM images of fabricated device. (c) Calculated capacitance of PhC-PD. The blue curve is calculated from the parallel-plate model. The red plots are results simulated by the finite-element method with a 3-D model. (d) Photocurrent versus optical power characteristic and eye diagram for 40-Gbit/s NRZ optical signals.**

We also studied an electro-absorption modulator (EAM) based on a PhC waveguide with the aim of realizing an ultralow-energy transmitter. An EAM has great potential for reducing the size, $C$, and driving voltage $V_{pp}$, compared with those of an electro-optic modulator involving the phase shift of light. However, the additional energy associated with the photocurrent flow under reverse voltage will increase the total electrical energy consumption. In this work, we demonstrated an EAM based on an InGaAsP-embedded PhC waveguide (Fig. 2a) [4]. This revealed a broadband optical modulation (Fig. 2b) and a dynamic modulation bit rate of up to 56 Gbit/s (Fig. 2c). The air-bridge structure and a device length of 100 μm or less result in a small $C$ of ≤ 13 fF while operating with a $V_{pp}$ of < 1 V, and this results in a charging energy of 1.6 fJ/bit. In particular, operation at a low reverse voltage of −0.2 V for a 3-dB extinction ratio effectively reduces the photocurrent energy. As a result, the total electrical energy needed for our EAM remains < 2 fJ/bit. This energy is lower than that of any waveguide EAM. These results show that our EAM overcomes the significant energy bottleneck exhibited by previous EAMs.

Our results suggest the potential for using our EAM and PD as a small-footprint low-energy transmitter and receiver, respectively. Monolithic integration with PhC nanolasers [5] that have a similar BH structure should be possible on the same InP-PhC platform, and even integration on silicon would be possible with a heterogeneous fabrication technique. This is an attractive way of constructing a dense nanophotonic functional architecture on a CMOS chip.

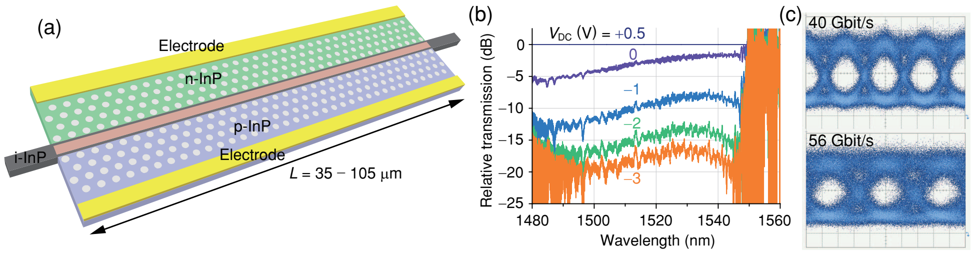


**Fig. 2 PhC-EAM. (a) Schematic of EAM structure. (b) Relative transmission spectra for different $V_{DC}$ in $L_{EAM}$ = 105 μm device. All the spectra are normalized with the spectrum of $V_{DC}$ = +0.5 V. (c) Eye diagrams at bit rates of 40 and 56 Gbit/s. The $V_{pp}$ was 2.0 V (swing from −1.5V to +0.5 V).**

## Acknowledgement

This work was supported by CREST, Japan Science and Technology Agency.

## References

[1] D. A. B. Miller, *Device requirements for optical interconnects to silicon chips*, Proceedings of the IEEE, vol. 97, pp. 1166-1185, 2009

[2] C. Debaes, A. Bhatnagar, D. Agarwal, R. Chen, G. A. Keeler, N. C. Helman, H. Thienpont, and D. A. B. Miller, *Receiver-less optical clock injection for clock distribution networks*, IEEE Journal of Selected Topics in Quantum Electronics, vol. 9, pp. 400-409, 2003

[3] K. Nozaki, S. Matsuo, T. Fujii, K. Takeda, M. Ono, A. Shakoor, E. Kuramochi, and M. Notomi, *Photonic-crystal nano-photodetector with ultrasmall capacitance for on-chip light-to-voltage conversion without an amplifier*, Optica, vol. 3, pp. 483-492, 2016

[4] K. Nozaki, S. Matsuo, T. Fujii, K. Takeda, M. Ono, A. Shakoor, E. Kuramochi, and M. Notomi, *Ultralow-energy InGaAsP modulators based on a photonic crystal waveguide/nanocavity involving the Franz-Keldysh effect*" in CLEO Pacific Rim, Busan, 27P2-69, 2015

[5] K. Takeda, T. Sato, A. Shinya, K. Nozaki, W. Kobayashi, H. Taniyama, M. Notomi, K. Hasebe, T. Kakitsuka, and S. Matsuo, *Few-fJ/bit data transmissions using directly modulated lambda-scale embedded active region photonic-crystal lasers*, Nature Photonics, vol. 7, pp. 569-575, 2013